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13. ABSTRACT *(Maximum 200 words)*

Established in 1981, the Center for Rotorcraft Education and Research at the University of Maryland has achieved international recognition as a center of excellence in rotorcraft engineering based on the quality and quanitity of its research output and advanced-degree recipients. In the process of growth, it has built an integrated team of rotorcraft dedicated research faculty and staff, a pipeline of high quality graduate students, and a group of specialized rotorcraft research facilities and instrumentation unmatched by any other university.

The Center carried out interdisciplinary research program built around four interrelated areas that advanced understanding and predictive capability in: Aerodynamics-unsteady aerodynamics, dynamic stall, and rotor/airframe interaction tests and analyses; Dynamics and Aeroelasticity-bearingless and composite rotor tests and analyses, and minimization of rotor/body vibrations by optimization techniques; Flight Dynamics and Control-control of the dynamic behavior of highly coupled rotor-fuselage configurations; Structures and Materials-structural integrity, energy absorption, and modeling of composite blades.

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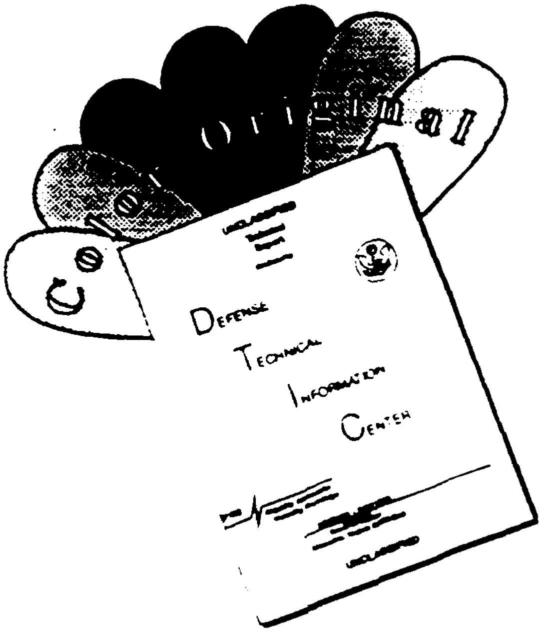

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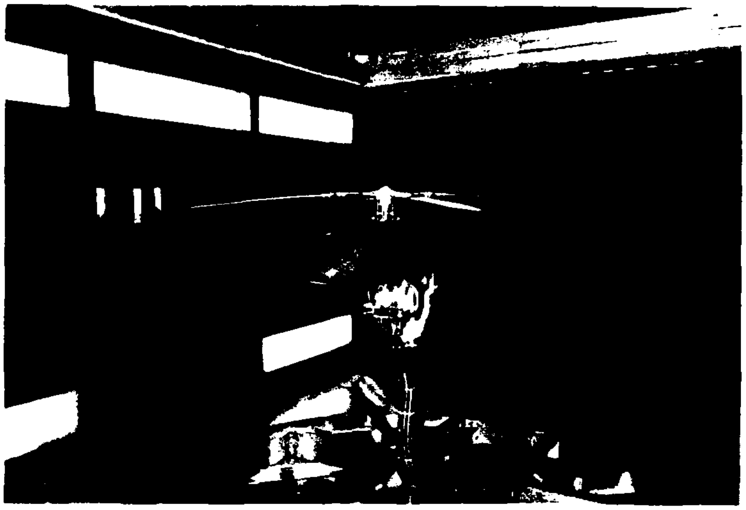
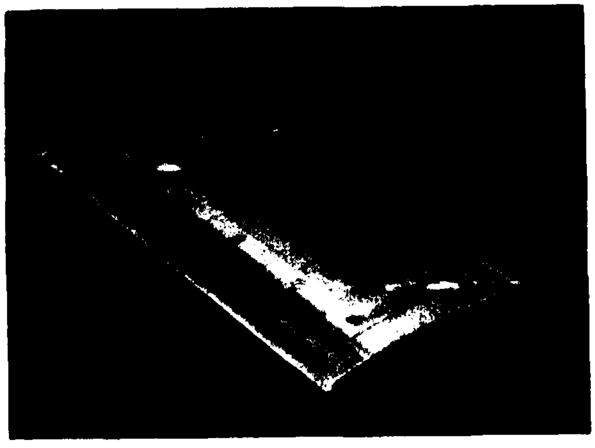


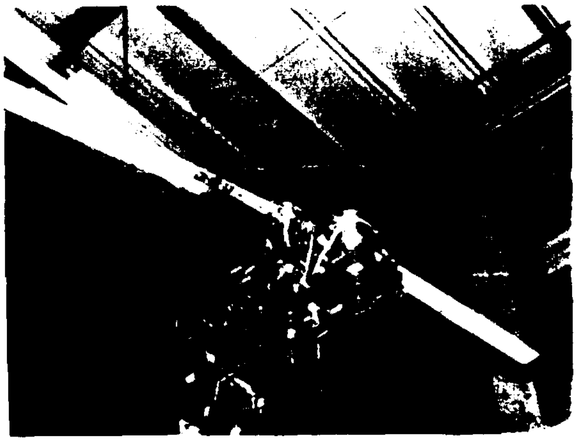
Center for Rotorcraft Education and Research

Final Report

1987-92

For Army Research Office
Contract No. DAAL-03-88-C-002





CENTER FOR ROTORCRAFT EDUCATION AND RESEARCH

Progress Report covering five years (1987-1992)

Established in 1981, the Center for Rotorcraft Education and Research at the University of Maryland has achieved international recognition as a center of excellence in rotorcraft engineering based on the quality and quantity of its research output and advanced-degree recipients. In the process of growth, it has built an integrated team of rotorcraft dedicated research faculty and staff, a pipeline of high quality graduate students, and a group of specialized rotorcraft research facilities and instrumentation unmatched by any other university.

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The research was carried out with extensive collaboration, involving joint planning, visits and mutual technical support between the Center, government laboratories, and the helicopter industry.

Inquiries are invited on any aspect of the report, and may be addressed to the undersigned or to the disciplinary group leaders as follows:

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Flight Dynamics	Roberto Celi	tel: (301) 405-1132
Aerodynamics	J. Gordon Leishman	tel: (301) 405-1126
Composite Structures	Anthony Vizzini	tel: (301) 405-1123

Inderjit Chopra, Director
Center for Rotorcraft Education
and Research
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fax: (301) 314-9001

TABLE OF CONTENTS

1.1 CURRENT FACULTY, GRADUATE STUDENTS AND STAFF

FACULTY

Inderjit Chopra - Professor and Director of CRER
Roberto Celi - Associate Professor
Alfred Gessow - Professor Emeritus
Sung Lee - Professor
J. Gordon Leishman - Associate Professor
Frederick A. Tasker - Assistant Professor
Anthony J. Vizzini - Associate Professor

ASSISTANT RESEARCH SCIENTIST

Ramesh Chandra

RESEARCH ASSOCIATE

Gunjit S. Bir

RESEARCH ENGINEERS

William R. Pogue, III
Dhananjay K. Samak
Mark O'Connor

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David Fleming
Christopher Jones
Christopher J. Niggemeier
Christopher Park
Ih-Cheng Shih
Anne M. Spence
Anita Tracy

GRADUATE ASSISTANTS (1992-93)

Ashish Bagai
Christopher M. Bothwell
Peter Chen

Ajay Divekar
Jennifer Gagliardi
Farhan Gandhi
Ranjan Ganguli
Gopal Kamath
Scott Kuczma
Judah Milgram
Erwin Moedersheim
David Platz
Jaewook Rhim
David Singh
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Vineet Sahasrabudhe
Steven Turnour
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Curtis Walz

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Mar, Daghir (Self-supported)
Walter Daniel (Naval Academy)
Mark Nixon (Army Langley)
Randall Smith (Praxis)
John Vorwald (NSWC)

DIRECTOR OF ADMINISTRATION

Maureen L. Meyer

SUPPORT STAFF

Carol Pironto - Account Clerk
Rebecca Sarni - Administrative Aide

1. INTRODUCTION

The Center for Rotorcraft Education and Research (CRER) at the University of Maryland, developed as a national center of excellence, is now recognized internationally as an outstanding forum for fundamental research and education in rotorcraft engineering. Established by a U.S. Army Research Office (ARO) contract in 1981 as a Center of Excellence in Rotary-Wing Technology, CRER has made innovative advances that address both the needs of the Army in satisfying its mission and the competitive challenges facing the U.S. helicopter industry. Simultaneously, the Center is training and educating a new generation of rotorcraft engineers in an environment designed to expand intellectual frontiers and achieve critical research objectives.

The Center has long recognized that the general field of helicopter engineering is becoming increasingly interdisciplinary, and that the traditional disciplinary boundaries are becoming less relevant. The most productive and relevant research will be that done by multidisciplinary groups of researchers who have both technical strength in the fundamentals, *as well as extensive background, expertise and personal commitment to work as a team on helicopter problems.*

The Center has been very productive in education and research. Since its inception, we have awarded 87 M.S. and 22 Ph.D. degrees. A measure of research productivity is the number of publications in refereed journals and conference proceedings. As the personnel and the organization of the Center have matured, the number of publications per year has reached very high levels, as shown in Figure 1. These publications are *all directly motivated by, and relevant to, helicopter applications*. Among the main ingredients for success, there are two of special importance. First, *faculty and students are all in the same academic department and physical location*. Even in an era of advanced telecommunications, there is no substitute for continuous personal contact among faculty and students and everyday exchange of ideas. This closeness and contact lead to the second ingredient for success: a team spirit engendered by mutual goals and the recognized dependence of each of the team members on the skills, ideas and enthusiasm of the others in the Center. The second is that the students of the Center are encouraged to become involved in research early in their careers, to prepare papers describing their work, and to present the results at professional meetings. Such an early start increases the exposure of students to the state of the art and to other experts in the field, and helps them become more productive sooner in their employment after graduation.

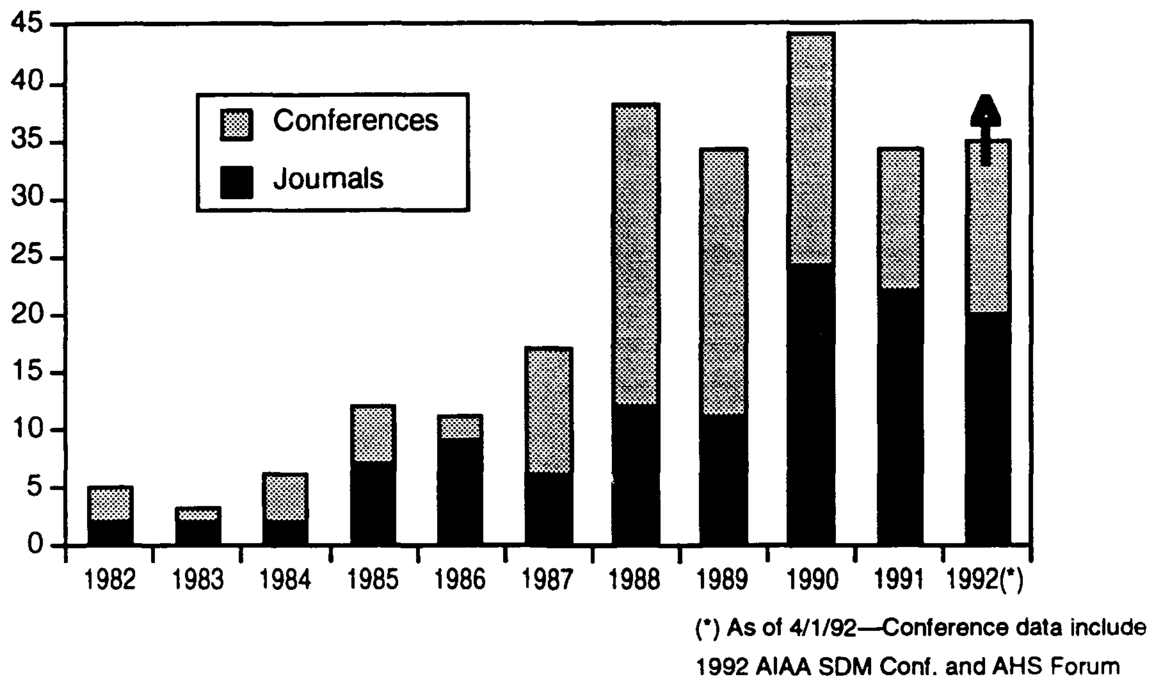

Figure 1 — Number of Publications in Journals and Conference Proceedings

It should be added that ARO funding has enabled us to offer many generous, prestigious fellowships and graduate research assistantships that, together with the quality of our educational programs, have helped attract a considerable number of highly qualified, rotorcraft interested students, the majority of whom are U.S. citizens. Several active duty U.S. Army officers have received degrees from the University of Maryland. We also make continuous and successful efforts to attract qualified women and minority students.

The Center thrives on a close and mutually supportive collaboration with the helicopter industry and with the NASA and Army laboratories. We have constantly pursued research that is both basic and relevant to the helicopter community. In the philosophy of CRER, fundamental studies that advance basic knowledge are the main building block of the research activities, consistent with the charter assigned to the Centers of Excellence by ARO. *We, however, have broadened our commitment further.* In collaboration with the helicopter industry and government laboratories, we have transferred the basic knowledge resulting from our studies into mathematical models and computer programs, that help directly the Army meet its goals, and the industry to provide improved products.

The basic research in rotor dynamics, aerodynamics, aeroelasticity, and structural optimization has provided the foundation for the University of

Maryland Advanced Rotorcraft Code (UMARC); research into the mathematics of flight dynamics formed the basis for the UM-Genhel flight simulation code; research in unsteady aerodynamics led to models incorporated in the Army 2GCHAS comprehensive analysis code, as well as in the codes of most of the U.S. helicopter manufacturers. In all cases, the Center has been active in informing U.S. industry and government laboratories of potentially useful results of its research, in sharing liberally such tangible products such as computer software and experimental data. Often this research cycle has included another very important component in the form of a student who, after working on the basic research with application to a practical helicopter problem, has found employment in the helicopter industry or in government laboratories. This is the most effective form of technology transfer.

In addition, within judicious boundaries suggested by security and industrial competition considerations, CRER has maintained extensive contacts with foreign helicopter manufacturers and government laboratories. Particularly, former graduates and visiting foreign scientists provide close ties with ONERA in France and DLR in Germany.

Over the years, CRER has developed an extensive array of experimental facilities. These include: an upgraded Glenn L. Martin 8.5-by-11 ft. wind tunnel; a rotor hover test facility; a 10-ft. diameter vacuum chamber; two fully instrumented rotor test rigs for articulated and bearingless rotor models; a state-of-the-art Composites Research Laboratory. During this period of reporting (1987-92) the vacuum chamber was made oprational, the rotor rig for bearingless rotors and hover tower were built and other facilities were upgraded. All the rotor and fuselage models required for our research activities can now be manufactured in-house. Not only do these facilities represent the result of a large, multi-year financial investment but, perhaps more importantly, they represent the result of a multi-year investment in intellectual resources.

The learning curve is steep and is often underestimated, especially in university environments. At Maryland, the intense and dedicated efforts of students, faculty, and staff have been such that all the experimental facilities are functioning, and used routinely as an integral, key part of the research and educational activities.

The research program of CRER is built around four interrelated thrust areas, namely: rotorcraft dynamics and aeroelasticity; aerodynamics; flight dynamics and control; and structures and materials. The program has equally balanced theoretical and experimental components. It is the philosophy of the Center that the fundamental research in disciplinary areas should be conducted in the context of a broad systems approach to the solution of helicopter engineering problems. Although the description of research tasks, in this document, follows for convenience along disciplinary lines, *we see each of the tasks as inherently interdisciplinary.*

In addition, Maryland has recently received a multi-year award from ARO to conduct multidisciplinary research in the area of *smart structures and materials*. Unique in the country, this (ARO/URI) program will focus the efforts of 14 faculty members and 20-25 graduate students from several departments of the University toward research of direct relevance to rotorcraft. The extensive research planned under the smart structures initiative, complements and greatly enhances the research activities of the Center.

The Center plans to expand its already broad range of research interests even further. The University of Maryland will hire two additional tenure-track faculty members who will carry out research in the areas of computational fluid dynamics and acoustics or control, with a specific focus toward helicopter applications. This is in addition to the new tenure-track faculty position already approved by the university in support of the smart structures research.

Recognizing the quality of the programs of the Center, the University of Maryland considers CRER as one of its highest priorities, and even in an era of severe budgetary constraints, committed substantial cost-sharing resources. The university commitment included partially waiving overhead, contributing faculty summer support, wind tunnel time, and funding of experimental facilities. It is due to the generous University cost-sharing contribution, as well as to the other funding that the Center attracted from sources such as NASA and Army laboratories, that it has been possible to sustain such a high level of research activity.

Task	Activities	Task Leader
Aerodynamics	**2.1** Unsteady Aerodynamics **2.2** Rotor/Airframe Interactional Aerodynamics	Leishman
Dynamics	**3.1** Ground/Air Resonance of Bearingless Rotors **3.2** Dynamics of Composite Rotors **3.3** Gas Response of Hingeless Rotors **3.4** Modeling of Rotor Unsteady Aerodynamics **3.5** Aeromechanical Stability **3.6** Higher Harmonic Control **3.7** Tail Rotor Dynamics **3.8** Aeroelastic Optimization **3.9** Coupled Rotor-Body Vibration **3.10** Development of UMARC	Chopra
Flight Dynamics and Control	**4.0** Flight Dynamics	Celi
Composite Structures and Materials	**5.0** Composite Structures and Materials **5.1** Structural Integrity **5.2** Multiaxial Energy Absorption **5.3** Finite Element Modeling of Composite Beams with Stiffness Couplings	Vizzini Lee

Table 1 — Summary of Tasks and Task Leaders

1.2 ROTORCRAFT DEGREES AWARDED

Ph.D.

Bi, Naipei - *Contributions to the Experimental Investigation of Rotor/Body Aerodynamic Interactions* - Leishman (May 1991) - Advanced Technologies, Inc.

Bir, Gunjit - *Gust Response of Articulated and Hingeless Rotors* - Chopra (November 1985) - Research Associate, University of Maryland

Crouse, Gilbert - *An Analytical Study of Unsteady Rotor/Fuselage Interaction in Hover and Forward Flight* - Leishman (December 1992) - Creative Design Concepts, Laurel, MD

Dull, Andrew L. - *Aeroelastic Stability of Bearingless Rotors in Forward Flight* - Chopra (July 1986) - Lt.Col. U.S. Army, Associate Professor, U.S. Military Academy, West Point

Elliott, Andrew S. - *Calculation of the Steadily Periodic and Gust Response of a Hingeless Rotor Helicopter Using 2-D Time Domain Unsteady Aerodynamics* - Chopra (October 1987) - Dynamics Group, Mechanical Dynamics Inc.

Fish, John - *Tensile Strength of Composite Structures with Internal Ply Drops and Free-Edge Effects* - - Lee (May 1988) - Lockheed Aircraft

Fledel, Shmuel - *Coupled Rotor/Airframe Vibration Analysis* - Chopra (December 1989) - Lt. Col., Israel Air Force

Haas, David - *Aeroelastic Characteristics of Circulation Control Wings* - Chopra (June 1989) - Aerospace Engineer, David Taylor Research Center

Hong, Chang-Ho - *Acroelastic Stability of Composite Rotor Blades in Hover* - Chopra (July 1985) - Associate Professor, Choong-Nam University, Korea

Jang, Jinseok - *Ground and Air Resonance of Bearingless Rotors in Hover and Forward Flight* - Chopra (August 1988) - Chief, Rotary-Wing Group, Agency of Defense Development, Korea

Lim, Joon - *Aeroelastic Optimization of a Helicopter Rotor* - Chopra (June 1988) - Dynamics Engineer, U.S. Army, Ames Research Center

Kim, Frederick - *Formulation and Validation of High-Order Mathematical Models of Helicopter Flight Dynamics* - Celi (December 1991) - Aerospace Engineer, NASA Ames Research Center

Kim, Ki C. - *Effects of Three Dimensional Aerodynamics on Blade Response and Loads* - Chopra (July 1990) - Research Engineer, U.S. Army, Aberdeen Proving Ground

Kim, Yong Hyup - *A Three-Dimensional Solid Element Model for Finite Rotation of Composite Shells* - Lee (October 1989) - Research Associate, University of Virginia

Nguyen, Khahn - *Application of Higher Harmonic Control Analysis forRotors Operating at High Speed and Maneuvering Flight* - Chopra (August 1989) - Aerospace Engineer, NASA Ames Research Center

Panda, B. - *Dynamic Stability of Hingeless and Bearingless Rotor Blades in Forward Flight* - Chopra (August 1985) - Research Engineer, Boeing Helicopters

Raghavan, Venkatraman - *Unsteady Force Calculator on Circular Cylinders and Elliptical Airfoils with Circulation Control* - Chopra (December 1987) - Research Engineer, NASA Ames

Smith, E.C. - *Aeroelastic Response and Aeromechanical Stability of Helicopers with Elastically Coupled Composite Rotor Blades* - Chopra (August 1992) - Assistant Professor, The Pennsylvania State University

Stemple, Alan D. - *Nonlinear Static and Dynamic Moeling of Composite Rotor Blades including Warping Effects* - Lee (May 1989) - McDonnell Douglas Helicopter Co.

Tasker, Frederick - *Nonlinear Damping Estimation From Rotor Stability Data Using Time and Frequency Domain Techniques* - Chopra (May 1990) - Assistant Professor, UMBC

Torok, Michael S. - *Rotor Loads Validation Utilizing a Couples Aeoelastic Analysis With Refined Aerodynamic Modeling-* - Chopra (August 1989) - Engineer, Sikorksy Aircraft

Wang, James M. - *Aeroelastic Analysis of Helicopter Rotors with Dissimilar Blades* - Chopra (November 1991) - Engineer, Sikorsky Aircraft

M.S. Thesis

Agnes, Gregory S. - *H• Vibration Control of Strain Actuated Composite Beams* - Lee (June 1990) - Wright-Patterson Air Force Base

Atanasoff, Hristo - *An Open Mold Foam Tooling Process for Manufacturing Stiffness-Coupled Composite Box Beams* - Vizzini (June 1991) - Swailes Assoc.

Ausserer, Michael F. - *Finite Element Analysis of Shell Structures with an Eighteen-Node Three Dimensional Solid Element Based on a New Mixed Formulation* - Lee (June 1986)- USAF detailed to FAA

Babuska, Vit - *An Expert System for Helicopter Conceptual Design* - Fabunmi (May 1987) - graduate student University of Texas at Austin

Barber, Randal - *Tilt Rotor Aeroelastic Stability Using Finite Element Rotor Model Characteristics* - Chopra (June 1987) - Aeronautical Engineer, CIA

Barrett, Ronald - *Intelligent Rotor Blade and Structures Development Using Directionally Attached Piezoelectric Crystals* - Chopra (May 1990) - Consultant

Benquet, Phillippe - *Calculated Dynamic Response and Loads for an Advanced Tip Rotor in Forward Flight* - Chopra (August 1988) - Scientist, French Ministry of Defense

Botting, Anthony - *The Effect of Tapering Geometry on the Delamination Strength of Composite Structures* - Lee (December 1990)

Farley, Roger - *Preliminary Design, Optimization and Evaluation of Man-Powered Helicopters* - Gessow (May 1986) - NASA Goddard

Fleming, David - *The Energy Absorption of Graphite/Epoxy Truncated Cones* - Vizzini (**91-92**) - Ph.D. , University of Maryland

Ghee, Terence - *An Experimental Investigation of Unsteady Circulation Control Aerodynamics of a Circular Cylinder* - Leishman (May 1990) - NASA Langley Research Center

Haas, David - *An Assumed Strain Nine-Node Finite Element for Fiber-Reinforced Composite Plates and Shells* - Lee (May 1985) - Aerospace Engineer, Naval Ship Research Development Center

Ingle, Steven - *The Effects of Higher Order Dynamics on Helicopter Flight Control Law Design* - Celi (July 1991)- Senior Handing Qualities Engineer, Boeing Helicopter Co.

Kammeyer, Mark E.- *Data Acquisition and Processing for Two-Component Laser Velocimetry in Periodically Unsteady Flows* - Winkelmann (December 1986) - Naval Surface Weapons Center

Kim, Yong H. - *A New Approach to the Finite Element Modeling of Beams with Warping Effect* - Lee (May 1986) - Research Associate, University of Virginia

Llanos, Antonio S. - *Delamination Prevention in Tapered Composite Structures Under Uniaxial Tensile Loads* - Lee (December 1989)- McDonnell Douglas Helicopter Co.

Matuska, D. - *Rotor Blade Dynamic Response and Structural Optimization of Vibration Reduction for Flap Mode* - Chopra (September 1983) - Design Engineer, Sikorsky Aircraft Co.

Mello, Olympio - *Unsteady Loads on Helicopter Lifting Surfaces* - Gessow (May 1988) - Graduate Student, Georgia Tech

Newman, Daniel I. - *Computer Aided Aircraft Configuration Layout Concept Validation: Design of the Crewstation Subsystem* - Gessow (December 1992) - Boeing Helicopter Co.

Noonan, Kevin - *Aerodynamic Design of a Helicopter Main Rotor Blade with Consideration of Flap-Lag Flutter in Hover* - Chopra (December 1985) - Engineer, U.S. Army Aerostructures Directorate, Langley

Ngo, Hieu - *Experimental Evaluation of Circulation Control Aerodynamics on a Cylindrical Body* - Chopra (December 1986) - Engineer, McDonnell Douglas Helicopter Co.

Ockier, Carl J. - *Engine-Rotor Interaction: A Dynamic Analysis in Hover* - Celi (August 1990) - DLR Germany

Ouillet, Pierre-Yves - *Prediction and Validation of Rotor Loads Using Nonlinear Unsteady Aerodynamics* - Chopra (June 1992) - Ministry of Defense, France

Picavet, P. - *Calculated and Measured Blade Airloads on a SA349-2 Gazelle* - Chopra (September 1992) - French Military

Pogue, William - *The Effects of Structural Tailoring via Edge Alteration on Free Edge Delamination of Composite Laminates* - Vizzini (December 1988) - Engineer, University of Maryland

Salzberg, Aaron - *Experimental Identification of Stiffness Coupling Terms in Composite Box Beams Manufactured by Thermal Expansion* - Chopra (December 1986) - Engineer, Naval Research Laboratory

Samak, D.K. - *Fabrication and Calibration of a Six Component Internal Strain Gage Balance* - Barlow (May 1987) - Engineer with the Department of Aerospace Engineering

Scardera, Michael - *Finite Element Shell Modeling with a Combination of Eight and Nine node Elements* - Lee (June 1986) - with U.S. Air Force

Schweisow, Brian - *Experimental Identification of Stiffness Coupling Terms in a Composite Beam* - Chopra (July 1985) - Engineer, Bell Helicopter Textron

Stemple, Alan D. - *Improved Finite Element Modeling of Composite Rotor Blades* - Lee (December 1986) - McDonnell Helicopters Co.

Tasker, Frederick - *Advanced Techniques for Structural Mobility Measurements* - Fabunmi (April 1986) - Asst. Professor, UMBC

Traversi, Andrea - *Development of a System to Conduct High Resolution Pressure Measurements at the Tip of a Semi-Infinite NACA 0012 Wing* - Winkelmann (December 1986) - Eliotos Helicopters, Italy

Tyler, Joseph - *An Analysis of Pitch and Plunge Effects on Unsteady Airfoil Behavior* - Leishman (May 1991) - Computer Sciences Corp., MD

van der Wall, Berend G. - *The Influence of Variable Flow Velocity on Unsteady Airfoil Behavior* - Leishman (May 1992) - DLR Germany

Vorwald, John - *Estimation of Damping Matrix from Frequency Response* - Fabumni (August 1986) - Naval Surface Weapons Center

Yeh, David - *Vortex Panel Calculation of Wake Rollup Behind a Large Aspect Ratio Wing* - Plotkin (May 1985) - a Ph.D. student at Stanford University

Zandieh, Ali - *Circulation Control of a Circular Cylinder Using Steady and Unsteady Jet Blowing* - Leishman (May 1992) Hughes, Herndon, VA

<u>M.S. Non-Thesis</u>

Aponso, Bimal - Barlow (1983), Systems Technology Inc.

Arterburn, David - Celi (May 1992), Captain U.S. Army, Instructor, U.S. Military Academy, West Point

Bagai, Ashish. - Leishman, (1992), Ph.D. student

Bate, J. - Chopra (1986), Sikorsky Aircraft Co.

Bruner, Christopher - Chopra (1989), U.S. Navy Pax River

Bupp, Robert - Lee (1992), Ph.D. student at Michigan University

Chan, Wai-Yip - Chopra (1991)

Chen, Peter - Chopra (1992), Ph.D. Student

Crouse, Gilbert L. - Leishman (1989), Ph.D. Student

Dirlik, Steve - Chopra (1990), David Taylor Research Center

Djordjevic, Slobodan - Chopra (1985), Auburn University

Elliott, Andrew E. - Chopra (1985), Ph.D. Student

Fledel, Shamuel - Chopra (1987), Lt. Col. Israel Air Force

Gandhi, Farhan - Lee (1991), Ph.D. Student

Ganguli, Ranjan - Chopra (1991), Ph.D. Student
Higman, Jerry - Barlow (1986), Graduate Student Georgia Tech.
Hong, C.H. - Chopra (1983), Ph.D. Student
Jang, Jinseok - Chopra (1984), Ph.D. Student
Kim, Frederick D. - Celi (1989), Ph.D. Student
Kim, Ki C. - Chopra (1987), Ph.D. Student
Kimata, Norman - Chopra (1990), Captain U.S. Army, Instructor U.S. Military Academy, West Point
Leifer, Joel H. - Chopra (1989), Consultant
Lenhardt, Darryl J. - Gessow (1989), U.S. Navy
Lim, Joon W. - Chopra (1987), Ph.D. Student
Milgram, Judah - Chopra (1992), Ph.D. Student
Montoya, Julio C. - Gessow (1989)
Mouritsen, Stephen - Barlow (1987), DLR Germany
Nguyen, K. - Chopra (1986), Ph.D. Student
Niggemeier, Christopher J. - Chopra (1992), Ph.D. Student
Panda, B. - Chopra (1984), Ph.D. Student
Park, Chul-Won - Vizzini (1989)
Pidaparti, Ramana - Lee (1985), Asst. Professor, Purdue University
Rhim, Jaewook - Lee (1992), Ph.D. Student
Sahasrabudhe, Vineet - Celi (1992)
Scardera, Michael - Lee (1987), U.S. Air Force
Scott, Mark W. - Barlow, Sikorsky Aircraft Co.
Shaffer, David - Leishman (1990), Captain U.S. Army
Smith, Edward C. - Chopra (1990), Ph.D. Student
Smith, Jodi A. - Chopra (1992), Penn State
Srinivas, Venkat - Chopra (1992), Ph.D. student
Staisloff, Michele - Lee (1990)
Torok, M. - Chopra (1986), Ph.D. Student
Turnour, Stephen - Celi (1992), Ph.D. Student
Vellaichamy, Senthi - Chopra (1993), Ph.D. Student
Tracy, Anita - Chopra (1991), Ph.D. Student
Wang, James - Chopra (1988), Ph.D. Student
Wunder, Bernard - Chopra (1988), Engineer, U.S. Navy, PAX River

1.4 Publications in Refereed Journals

1993

1. Bi, N., Leishman, J.G., and Crouse, G.L., "Rotor Wake/Body Interactions in Forward Flight," to appear in the *Journal of Aircraft*, Jan./Feb. 1993.

2. Chandra, R. and Chopra, I., "Structural Modeling of Composite Beams with Induced Strain Actuation," accepted for publication in *AIAA Journal*, 1993.

3. Chandra, R. and Chopra, I., "Dynamic Testing of Thin-Walled Composite Box Beams in a Vacuum Chamber," accepted for publication in the *Journal of Aircraft*.

4. Chandra, R. and Chopra, I., "Vibration Characteristics of Composite I-Beams with Elastic Couplings Under Rotation," accepted for publication in *AIAA Journal*, 1993.

5. Fleming, D.C. and Vizzini, A.J., "Tapered Geometries for Improved Crashworthiness Under Side Loads", *Journal of the American Helicopter Society*, Vol. 38 (1), January 1993, pp. 38-44.

6. Kim, F.D., Celi, R., and Tischler, M.B., "Forward Flight Trim Calculation and Frequency Response Validation of a High-Order Helicopter Simulation Model," to appear in the *Journal of Aircraft*, July-August 1993.

7. Kim, F.D., Celi, R., and Tischler, M.B., "High Order State Space Simulation Models of Helicopter Flight Mechanics," accepted for publication in the *Journal of the American Helicopter Society*.

8. Ingle, S. and Celi, R., "Effect of Higher Order Dynamics on Helicopter Flight Control Law Design," accepted for publication in the *Journal of the American Helicopter Society*.

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2.0 AERODYNAMICS

Over the last five years, the aerodynamics program has concentrated on two main areas: 1. The analysis and modeling of unsteady aerodynamics and dynamic stall, and 2. Rotor/airframe interactional aerodynamics. The overall objectives have been to provide an improved understanding of the problems, and to devise improved predictive models that can be used in comprehensive rotor codes.

2.1 Unsteady Aerodynamics

The overall objective of the unsteady aerodynamics work has been to develop a more realistic and comprehensive mathematical model for the blade element unsteady aerodynamics (i.e., the lift, pitching moment and drag) and in a computational form that can be included within modern rotor loads and aeroelasticity analyses. Most previous unsteady aerodynamic methods were based on incompressible flow assumptions, with simple "steady flow corrections" for compressibility effects. Further, the dynamic stall modeling was very primitive, and was often based on a simple resynthesization process using measured unsteady airloads as a basis. Therefore, the overall aerodynamic modeling lacked rigor when applied to most rotor problems, particularly rotor loads and aeroelasticity. The objectives of the present research have been to remove many of the limitations inherent in existing unsteady aerodynamic models.

The basis of the new method is an indicial response and linear superposition method. While this basic approach is not new in itself, there are several features of the model that are unique. Since there are no known exact solutions for the indicial response in subsonic flows, new indicial functions have been derived on the basis of both exact linear theory and experimental data. The exact theory comprises a solution to the wave equation for small values of time, and the experimental data is taken from oscillating airfoils in pitch and plunge. By also converting the assumed forms of the indicial response into the frequency domain, these results have been used by means of an optimization process to extract the indicial lift and moment functions for a range of Mach numbers appropriate to rotorcraft.

The "dynamic stall" or nonlinear part of the model consists of a cascade of individual subsystems, each of which represents a physical part of the unsteady separation and dynamic stall process. The benefits of this approach are obvious, since the union of a series of separate subsystems is easier than modeling the system as a whole. It also should be mentioned that for this part of the model there is a need to draw a compromise between physical accuracy and computational efficiency. Therefore, each subsystem is modeled at a sufficiently basic level of approximation to provide a realistic representation of the phenomenon. For example, the primary degree-of-freedom in the modeling is the dynamic separation point. Since it is known that for high Reynolds number, the boundary layer equations take on the form of a first order system, the time-dependent behavior of the separation point is related to the outer solution (lift and pressure distribution) through a first order equation with an empirically derived time constant.

The linear part of the solution is coupled to each of the nonlinear parts, both directly and by feed forward loops whose effect depends on state related events. For example, the onset of leading edge separation is initiated by a adverse leading edge pressure gradient criterion. This activates the feed forward loops that alter the time constants representing the behavior of other subsystems. This form of approach allows a progressive transition from the static to the dynamic stall characteristics.

This method of approach has been shown to give excellent predictions when compared with experimental measurements. The modeling has also been extended by validation with experimental measurements to include the effects of swept (yawed) flow, and also the effects of both pitch and plunging (heave) motions on the stall process. The model has been used (in some form) by nearly all US helicopter manufacturers, and has been incorporated within the Second Generation Comprehensive Helicopter Rotor Analysis (2GCHAS). Several publications have resulted from this work, and the most significant are outlined below.

2.1.1 Validation of Approximate Indicial Aerodynamic Functions for Two-Dimensional Subsonic Flow

This work forms the foundation for the unsteady aerodynamic model. The objective has been to derive approximations for the two dimensional indicial aerodynamic responses due to step changes in angle of attack and pitch rate. These responses have been generalized to account for compressibility effects up to a Mach number of 0.8. Using the Laplace transform method, the assumed form of the indicial functions were manipulated to produce explicit solutions for idealized harmonic forcing, such as oscillations in pitch and plunge. These explicit solutions are subsequently compared with experimentally obtained pitch and plunge aerodynamic data in the reduced frequency domain. The results of this comparison are used to relate back and substantiate the generalization of the compressible indicial lift and moment functions.

2.1.2 Modeling of Subsonic Unsteady Aerodynamics for Rotary Wing Applications

In this work, practical applications of the previously derived two-dimensional subsonic indicial response functions are discussed. These indicial functions are used with the Duhamel superposition principle to obtain the unsteady lift, drag and pitching moment on an airfoil. Numerical procedures are presented to account for arbitrary motion of a rotor blade section, as well as encounters with gusts or vortices. These procedures are presented in both discrete-time and continuous-time (state-space) forms, either of which are suitable for practical application to comprehensive rotary wing performance and aeroelasticity analyses. The formulation represents an economical and accurate bridge between incompressible quasi-steady aerodynamics and more elaborate computational methods. An extensive validation of the approach is conducted with experimental data and other theoretical results.

2.1.3 A Semi-Empirical Model for Dynamic Stall

A semi-empirical model is formulated to represent the unsteady lift, drag and pitching moment characteristics of an airfoil undergoing dynamic stall. The model is presented in a form which is consistent with the previously described indicial formulation for the unsteady aerodynamics under attached flow conditions. The onset of vortex shedding during dynamic stall is represented using a criterion for leading edge or shock induced separation based on the attainment of a critical leading edge pressure. The induced vortex lift is represented empirically along with the associated pitching moment which is obtained by allowing the center of pressure to move in a time dependent manner during dynamic stall. Significant nonlinearities in the airfoil behavior associated with trailing edge separation are represented using a Kirchhoff flow model in which the separation point is related to the airfoil behavior. These effects are represented in such a way as to allow progressive transition between the dynamic stall and the static stall characteristics. It is shown how the above features may be implemented as an algorithm suitable for inclusion within rotorcraft airloads or aeroelasticity analyses. Validation of the model is presented with force and moment data from two-dimensional unsteady tests on the NACA 0012, HH-02 and SC-1095 airfoils.

2.1.4 Modeling Sweep Effects on Dynamic Stall

This work represents an extension of the basic dynamic stall model described previously. A semi-empirical procedure is described to represent the effects of blade sweep (yaw) angle on the airloads during dynamic stall of a typical blade section. The procedure is consistent with the numerical algorithms used to model for lift, pitching moment and drag prediction within the context of helicopter rotor aeroelasticity and performance analyses. It has been concluded from this study that sweep angle primarily affects the nonlinear airloads by modifying the local development of trailing edge flow separation; the subsequent behavior of the airloads, under both steady and unsteady conditions, appear as a consequence. Justification of the modeling is conducted with experimentally obtained dynamic stall data for a NACA 0012 airfoil oscillating in pitch at a Mach number of 0.4 with steady sweep angles of 0 and 30 degrees. Excellent correlations were obtained with the test data, and provide increased confidence in the validity of the unsteady aerodynamic model for the helicopter rotor environment. A preliminary method is also suggested to account for time dependent sweep effects.

2.1.5 A State-Space Representation of Unsteady Airfoil Behavior

This work represents an alternative formulation of the unsteady aerodynamic model described previously. In the first version of the model, a one step recursive process had been used to compute the unsteady loads for arbitrary forcing conditions. However, this approach is not always suitable for many forms of aeroelasticity calculations. Therefore, an equivalent state-space method has been formulated to model the unsteady lift, moment and drag acting on a two-dimensional airfoil operating under attached flow conditions. Starting from suitable generalizations and approximations to the aerodynamic indicial functions, the unsteady airloads due to an arbitrary forcing are represented in differential equation form. This model is in a form compatible with many aeroelastic analyses of both fixed-wing and rotary-wing systems. Again, an important feature of the method is the inclusion of flow compressibility effects. The method is validated against experimentally obtained aerodynamic loads for two-dimensional airfoils undergoing oscillatory plunge, oscillatory pitch and steady pitch rate (ramp) forcing at various Mach numbers below stall.

2.1.6 Transonic Aeroelasticity Analysis using State-Space Unsteady Aerodynamic Modeling

This work represents an application of the state-space unsteady aerodynamic modeling. An aeroelastic analysis is conducted on a two degree-of-freedom airfoil in transonic flow using a generalized state-space approximation for the unsteady aerodynamics. The aerodynamic representation is validated against computational fluid dynamic solutions for angle of attack oscillations up to Mach numbers of 0.875 and at reduced frequencies up to 1.0. Despite the inherent nonlinear nature of transonic flow, it is shown that a linear finite-state model with as few as eight states can provide a good approximation to the unsteady lift and moment behavior if appropriate allowance is made for Mach number effects on the airfoil's static lift-curve-slope and mean aerodynamic center. It is shown how the aerodynamic representation can be coupled to the structural equations of a typical airfoil section with bending and torsional degrees-of-freedom. The stability of the resulting aeroelastic system is determined by eigenanalysis. This aeroelastic analysis is shown to be in excellent agreement with calculations performed using more sophisticated unsteady aerodynamic theories.

2.1.7 Analysis of Pitch and Plunge Effects on Unsteady Airfoil Behavior

The majority of angle of attack variations seen by a typical blade element on a rotor is due to flapping. At the simplest level of approximation, this is equivalent to a plunging or heaving type of motion. However, most existing mathematical models have been derived and/or validated only on the basis of pitch oscillations. Therefore, an analysis was conducted into the effects of pitch versus plunge forcing on unsteady airfoil behavior. Experimental measurements of unsteady airloads were analyzed in conjunction with classical unsteady airfoil theory and a semi-empirical model for dynamic stall. The separate contributions to the unsteady airloads due to angle of attack and pitch rate are shown to be the key variables governing aerodynamic damping, the onset of leading edge separation, and dynamic stall. Correlations with experimental data have been shown at various Mach numbers.

2.1.8 Improved Indicial Lift Approximations for Two-Dimensional Subsonic Flow as Obtained from Oscillatory Measurements

This work represents an extension of the previous indicial response work, where an improved representation of the indicial functions are derived. The approach is used to obtain generalized approximations to the indicial lift response due to angle of attack and pitch rate in two-dimensional subsonic flow. The effects of pitch axis are also examined. Starting from an assumed representation, the approximations are accomplished by means of a nongradient optimization algorithm in which the coefficients of the approximation are free-parameters. The optimization is subject to prescribed constraints in terms of the known initial and asymptotic behavior of the indicial response, and by requiring the response duplicate the known exact (analytic) solutions at earlier values of time. The approach is applied to extract the intermediate forms of the indicial lift response, generalized in terms of Mach number and pitch axis location, from experimental measurements of the unsteady lift in the frequency domain. It is subsequently shown that the derived forms of the indicial response provides a suitable basis for the formulation of a theory for the unsteady lift on airfoils undergoing arbitrary motion or encountering an arbitrary gust field in subsonic flow.

2.1.9 The Influence of Variable Flow Velocity on Unsteady Airfoil Behavior

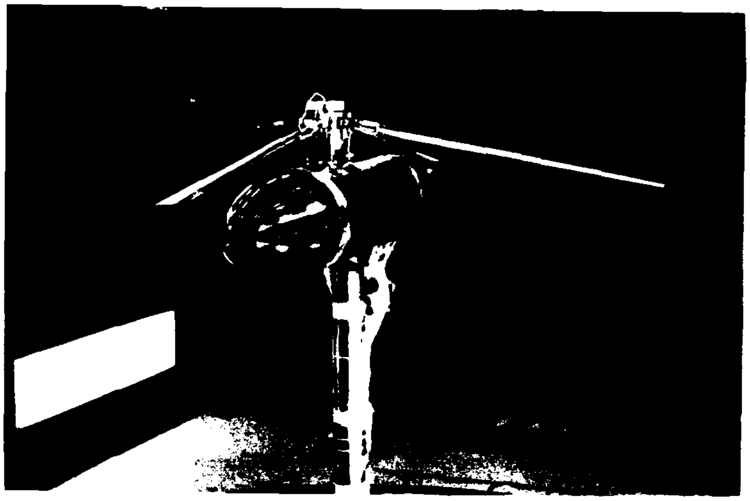
In a helicopter rotor environment, the blade element encounters not only variations in angle of attack and pitch rate, but also variations in incident velocity and Mach number. Even if the airfoil is held at a constant orientation relative to the oncoming flow, variations in incident velocity produce variations in unsteady lift. Therefore, the effects of an oscillating free-stream on the unsteady aerodynamics of an airfoil in incompressible flow is examined. Existing theories are reviewed, and their simplifications and limitations are properly identified. An improved exact theory for an airfoil undergoing a combination of harmonic pitching, plunging and fore-aft motion is presented. One objective of the work is to examine the significance the effects of unsteady local velocity fluctuations in a rotor loads or aeroelastic analysis in forward flight. To this end, an arbitrary motion theory is also given, which comprises a numerical solution to Duhamel's integral with the corresponding indicial response. The results are also validated against predictions made by a modern CFD (Euler) code.

2.2 Rotor/Airframe Interactional Aerodynamics

The overall objectives of the rotor/airframe interaction studies were twofold. First, to experimentally identify the important mechanisms responsible for the aerodynamic interference effects that exist between a helicopter fuselage and rotor. Second, to mathematically model these effects at a level of approximation that potentially could be included within a comprehensive rotor analysis.

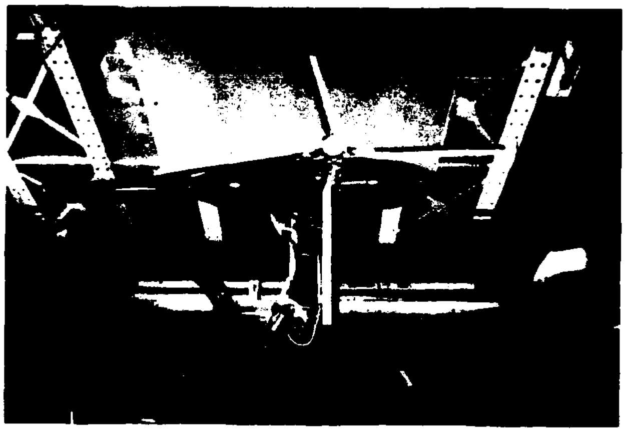
The motivation for this work is clear. Because of design trends which show increasing blade loading coefficients and decreasing clearances between the main rotor and the fuselage, the aerodynamic interactional effects on helicopters have been identified as a major source of unsteady loads and vibrations. In addition, rotor/empennage interference effects have been identified as a source which can adversely affect the handling qualities of the aircraft. Furthermore, not only does the rotor affect the airframe loads, but the airframe affects the rotor loads and performance. This latter effect is poorly understood, and more recently has been the main subject of investigation.

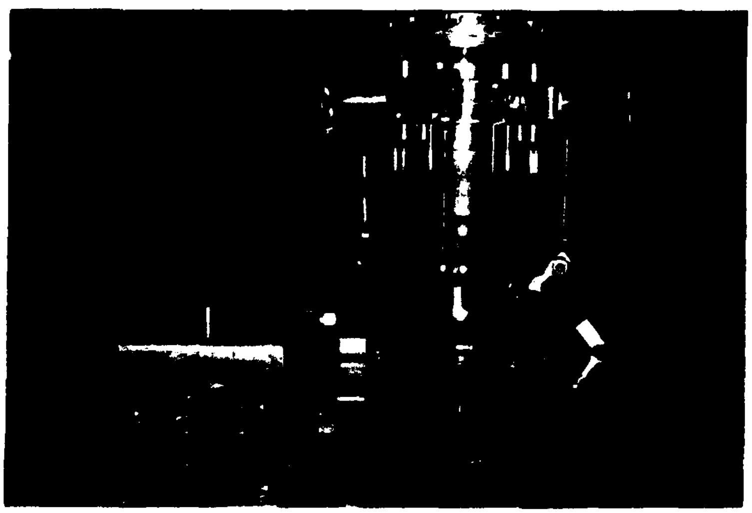
To examine these effects experimentally, a series of systematic tests have been conducted (over a period of four years) in the Glenn L. Martin wind-tunnel. The objectives have been to more clearly identify the underlying mechanisms associated with individual phenomena. In previous experiments, many of the phenomena have been present at once, making the isolation of single phenomena very difficult. For the present experiments, a four bladed articulated rotor rig has been used, along with a body of revolution representing the fuselage but with a helicopter fuselage like shape. An auxiliary wing has been used to examined rotor/empennage interactions. Loads have been measured on the rotor and the fuselage using an independent force balance system. In addition, both steady and unsteady pressure loads have been measured on the fuselage and the associated lifting surface. An extensive flow field mapping survey has also been undertaken. Extensive flow visualization has been conducted using the wide-field shadowgraph technique. The tests have been conducted at various combinations of advance ratios, rotor thrusts, and tip-path-plane angles of attack.



Articulated rotor/airframe set-up for rotor/body interactional tests in Glenn L. Martin Wind Tunnel

Rotor/body interaction tests being performed in hover test rig. Screen in background is used for wide-field shadowgraph flow visualization.





Details of 4-bladed Mach-scaled articulated rotor, showing hub, swashplate, pitch links and 6-component balance

The results from this series of controlled experiments have enabled an improved understanding of the interactional effects of the rotor on the fuselage aerodynamics and the effects of the fuselage on the rotor behavior. Also, some preliminary work has been performed to examine the effects of the rotor on the loads of a lifting surface, for example, representing a horizontal tail. The results have been used to validate and improve the predictive capability of analytical models. Several mathematical models have been examined, and have been incorporated into a research code called MURFI (Maryland Unsteady Rotor Fuselage Interaction model). The experimental data have also been used by several other organizations, including Continuum Dynamics Inc., Analytical Methods Inc., NASA (for PMARC), ONERA, and UTRC. Several publications have resulted from the research work and are briefly described below.

2.2.1 Aerodynamic Interactions between a Rotor and a Fuselage in Forward Flight

This paper documents some of the results from the first wind-tunnel test. Experiments were conducted to examine the overall interactional aerodynamic effects between the rotor and the fuselage. Tests were conducted on the isolated fuselage, isolated rotor and on the rotor and fuselage combination. Independent strain-gauge balance loads were obtained on the fuselage and rotor along with both steady and unsteady pressure measurements on the fuselage. Data were obtained for various combinations of advance ratio, shaft tilt and rotor thrust. The results indicate that while the rotor wake produces large changes in the mean loads on the fuselage, unsteady pressure fluctuations due to blade passage and wake impingement are the most dominant form of loading. The magnitude of the unsteady loads on the fuselage were found to be primarily a function of rotor thrust. Results also show significant effects of the fuselage on the rotor. When operating at low advance ratio, the presence of the fuselage produces an increase in rotor thrust for a given collective pitch and a reduction in rotor power for a given thrust. The wake skew angle was found to be an effective parameter governing the magnitude of the time-averaged interactional loads on both the rotor and fuselage.

2.2.2 Analysis of Unsteady Pressures Induced on a Body in the Vicinity of a Rotor

This paper documents a more detailed series of experiments on the problem. An analysis was conducted into the unsteady surface pressures measured on a body in proximity to a thrusting helicopter rotor. Unsteady pressures were measured at strategic points on the body in low speed forward flight at various combinations of advance ratio, rotor thrust and tip-path-plane (TPP) angle. It was found that the local values of unsteady pressure were significantly altered by small changes in rotor thrust and advance ratio, TPP angle variations having a much smaller effect. Four characteristic pressure signatures, representative of (1) blade passage, (2) close wake interactions with the body, (3) wake impingement on the body and (4) post-wake impingement were distinguished. These classifications were supported by correlations with shadowgraphic flow visualization of the rotor wake/body interaction as well as unsteady potential flow models. This general classification of the unsteady fuselage pressure signatures has permitted a greater physical understanding of the overall airloads and possible mechanisms responsible for the interactional effects between a helicopter rotor and its fuselage. Details of the wake impingement process on the body are also discussed.

2.2.3 Investigation of Rotor Tip Vortex Interactions with a Body

This paper documents work on the tip vortex/body surface impingement problem. Experiments were conducted to examine rotor tip vortex interactions with a body in low speed forward flight. Unsteady pressure measurements were made at points along the top and around the circumference of the body surface. Flow visualization of the rotor wake was performed using the wide-field shadowgraph method. Considerable insight into the tip vortex interaction processes was obtained by correlating the pressure loads with the vortex trajectories as they approached, distorted and impinged on the body surface. Unsteady potential flow theory was explored as a means of predicting the unsteady pressure loads on the body surface, using prescribed tip vortex trajectories measured from flow visualization. The results have shown that the process of tip vortex interaction with a body can be divided into three regimes, namely: (1) close tip vortex/body interactions, which is an inviscid flow regime, (2) vortex/surface impingement, and (3) post vortex/surface impingement; the latter involves viscous effects. The results have also shown that the pressures at points on the body exhibited a high sensitivity to tip vortex convection speed and location, which makes the general prediction of such interactional phenomena difficult with existing rotor/airframe interaction models.

2.2.4 Experimental Study of Rotor Wake/Body Interactions in Hover

Since rotor/airframe interactions are particularly acute in hovering flight, a series of experiments were conducted into this specific problem. Experiments were conducted on a hover tower to document the tip vortex geometries and interactional effects between a hovering rotor and a body representing a simplified helicopter fuselage. The wide-field shadowgraph technique was used to visualize the rotor tip vortices and to obtain quantitative information on the trajectories, with and without the presence of the body. It was found that the effects of the body caused significant changes to both the radial contraction and axial displacements of the tip vortices compared to the isolated case. Direct impingement of the tip vortices on the body surface was also observed, and found to cause large local wake deformations. The rotor performance was significantly affected by the body, producing a higher figure of merit relative to the isolated case.

2.2.5 Fundamental Studies of Rotor Wakes in Low Speed Forward Flight using Wide-Field Shadowgraphy

This work documents some fundamental studies into the structure of rotor wakes in forward flight. Experiments were conducted using the wide-field shadowgraph method to visualize the wake from a helicopter rotor in low speed forward flight. The experiments were performed with an isolated rotor and with a body representing a helicopter fuselage. Particular attention was paid to documenting the isolated rotor wake geometry, blade vortex interaction phenomena near the rotor plane, the distortion made to the wake due to the presence of the body, and detailing the interaction of the tip vortices with the body surface. Quantitative measurements were made of the wake trajectories as functions of wake age. Estimates of the tip vortex core radius were also made. The results have provided many details of the rotor wake structure that are useful for validating rotor wake and rotor/body interactional models in forward flight. The use of the wide-field shadowgraph method offers an important tool for visualizing rotor wake vortices, and helping to understand the complex three-dimensional nature of rotor wakes in forward flight.

2.2.6 Measurements of a Rotor Flow Field and the Effects on a Fuselage in Forward Flight

Wind tunnel experiments were conducted to quantify the induced flow field in the vicinity of a helicopter rotor in forward flight. Tests were performed with an isolated rotor and with a rotor/fuselage combination at advance ratios of 0.075, 0.10 and 0.20. Measurements of the time-averaged total pressure, dynamic pressure and flow angularity were made using an array of miniature seven-hole probes. Data were obtained at a total of 2,688 points in three planes extending below and behind the rotor. The results show that the rotor produces significant increases in total pressure within the boundaries of the rotor wake. The total pressure was distributed in a highly non-uniform manner, both laterally and longitudinally, and was biased primarily towards the rear of the disk. At low advance ratios, the rotor induced velocities were principally downward and produced a download on the fuselage. As the advance ratio was increased however, the induced velocities became quickly streamwise and resulted in an upforce on the fuselage. Considerable changes in the fuselage pitching moments were also obtained due to the relocation of the wake boundaries. The rotor wake boundaries and distribution of induced inflow were only slightly affected by the presence of the fuselage.

2.2.7 Experimental Investigation of Rotor/Lifting Surface Interactions

Experiments were conducted to study the aerodynamic interactions between a rotor and a fixed lifting surface. A low aspect ratio rectangular wing was positioned at different locations in a rotor flow field to simulate the aerodynamic environment encountered by the wings of tilt-rotors, or by the empennage of helicopters. Steady and unsteady pressure measurements were made on the wing at various chordwise and spanwise stations for various rotor thrusts and advance ratios. Flow visualization was performed using the wide-field shadowgraph method, which helped to identify the locations of the rotor wake relative to the wing. The results have shown that the lifting surface operates in a highly unsteady three-dimensional flow environment, with regions of partial or complete flow separation. In addition, large unsteady loads were induced on
the wing due to rotor blade passage effects and/or induced loads due to close passage or impingement of the rotor tip vortices on the wing surface.

2.2.8 Theoretical and Experimental Study of Unsteady Rotor/Body Aerodynamic Interactions

Theoretical and experimental results are presented which clarify the nature of the unsteady aerodynamic interactions between a rotor/body combination in forward flight. Experimental measurements of the time-dependent body pressures are compared with predictions made by two models of the body, rotor and its wake system. The first model is a fairly elementary representation using a vortex ring wake and a one-dimensional surface model for the body. The second model consists of a more sophisticated unsteady source panel representation for the body, a lifting line for the rotor, along with a prescribed wake system. Appropriate unsteady terms are included in these analyses. The results show that the unsteady pressure loads on a large part of the body are dominated by the periodically induced pressure field due to the rotor itself. These loads are well predicted using either model. Additional unsteady effects on the body are due to either close passage or direct impingement of the rotor wake vortices. It is shown that if the rotor wake geometry is accurately modeled, then the unsteady pressure signatures can be readily predicted in all locations except where the wake impinges directly on the body. In such cases, viscous interactions appear to play a strong role in the process and are not easily predicted.

2.2.9 Interactional Aerodynamic Effects on Rotor Performance in Hover and Forward Flight

A theoretical analysis has been conducted into the significance of rotor/body aerodynamic interactions on rotor performance and blade loads. Results from the analysis are compared with measurements from wind tunnel tests that were conducted on a rotor/body combination in hover and at advance ratios between 0.05 and 0.25. The experimental results showed significant changes in rotor thrust and power requirements with the introduction of a body to the flow field. The theoretical analysis has been conducted to help explain the aerodynamic mechanisms involved. A fully unsteady potential flow model of the rotor and body was developed. The wake models consisted of a free wake methodology, as well as a standard prescribed wake, both coupled with a novel treatment of the rotor wake/body interaction process. These wake models were combined with an unsteady panel model of the body and a rigid rotor analysis to allow fully interactive trim calculations. The theoretical analysis has shown significant changes in the inflow distribution through the rotor disk, as well as large associated changes in the lift and inflow distribution due to the presence of the body, and which explain the source of measured effects on the rotor performance.

As a bi-product of the research into rotor/airframe interactions, several new techniques have been developed. Also, several other issues have been explored. Two additional papers have been written that document some of this work.

2.2.10 Improved Wide-Field Shadowgraph System for Rotor Wake Visualization

This paper describes the development of an improved wide-field shadowgraph technique for helicopter or tilt rotor wake visualization. The improved system makes use of a beam splitter and provides several significant advantages over previously used wide-field shadowgraph set-ups. The primary advantage is that the technique can be used to effectively collocate the light source and the recording camera on the optical axis. This eliminates various optical problems associated with previous wide-field shadowgraph systems. A secondary advantage is that the system also can be arranged to permit simultaneous viewing by two separate cameras. The improved system significantly increases the utility of the shadowgraph method for rotor wake visualization in hover or forward flight, as well as for other flow visualization situations with relatively weak density gradients and where wide fields of view are necessary.

2.2.11 Flow Visualization of Compressible Vortex Structures using Density Gradient Techniques

In this paper, mathematical results are derived for the schlieren and shadowgraph contrast variation due to the refraction of light rays passing through two-dimensional compressible vortices with viscous cores. Both standard and small-disturbance solutions are obtained. It is shown that schlieren and shadowgraph produce substantially different contrast profiles. Further, the shadowgraph contrast variation is shown to be very sensitive to the vortex velocity profile and is also dependent on the location of the peak peripheral velocity (viscous core radius). The computed results are compared to actual contrast measurements made for rotor tip vortices using the shadowgraph flow visualization technique. The work helps to clarify the relationships between the observed contrast and the structure of vortical structures in density gradient based flow visualization experiments.

3.0 DYNAMICS

In the past five years, there has been extensive research activities in the helicopter dynamics discipline. These included ground/air resonance of bearingless rotors, dynamics of composite rotors, gust response of hingeless rotors, modeling unsteady aerodynamics in rotor analysis, aeromechanical stability, higher harmonic control, tail rotor dynamics, aeroelastic optimization, coupled rotor-body vibration and development of UMARC. Many of these research tasks had considerable overlap with other disciplines. For example, dynamics of composite rotors is closely tied with ongoing research in the composite structures discipline (Chapter 5); modeling of unsteady aerodynamics in rotor analysis uses the tools developed in rotor aerodynamics discipline (Chapter 2); tail rotor dynamics interacts with aerodynamics and flight stability and control disciplines (Chapters 2 and 4). Prior to this period (before 1987), much effort was focused to develop new facilities such as bearingless rotor rig, bearingless rotor model, vacuum chamber and composite research laboratory. Many new instrumentation and data acquisition system were acquired. During recent five years, these facilities were gainfully used to complement ongoing research and expand into many new challenging problems.

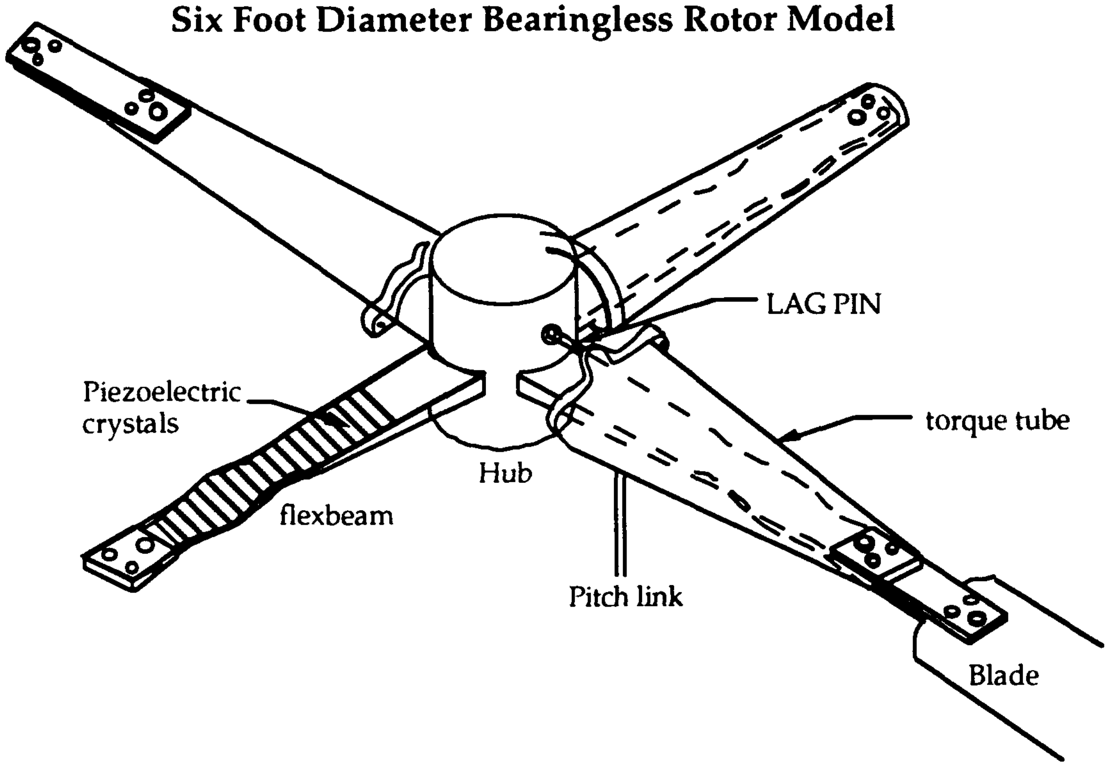
3.1 GROUND/AIR RESONANCE OF BEARINGLESS ROTORS

In recent years there has been growing interest in bearingless rotors because of design simplicity (lower parts count), better maintenance and more control power. A bearingless rotor is one special example of a hingeless rotor in which flap and lag hinges as well as the pitch bearing are eliminated. The distinguishing feature of the bearingless rotor is a torsionally soft flexbeam located between the blade and the hub. Pitch control to the main blade is applied through a torsionally stiff torque tube by rotating it with pitch links, which in turn twist the flexbeam. The analysis of a bearingless rotor blade is more involved than that of a hingeless or an articulated rotor blade because of the redundancy of load paths at the root and nonlinear bending-torsion coupling effects. To achieve manageable bending stresses (dynamic) on the blade, bearingless rotors are designed as soft-inplane rotors. This makes these rotors susceptible to aeromechanical instabilities in the air (air resonance) as well as on the ground (ground resonance). Air resonance is caused by the coupling of the low frequency blade flap and lag modes with rigid body airframe modes. Ground resonance is caused by coupling of the low frequency blade lag modes and landing gear modes. Both these instabilities are important for the design development of a bearingless rotor, and therefore accurate analytical tools must be developed to predict these.

The objective of this research was to formulate analytical tools to analyze the ground and air resonance stabilitу advanced bearingless rotors, and to correlate the predicted results with data measured on a model rotor for different flight conditions. For stability data, it was planned to carry out systematic testing of a Froude-scaled bearingless rotor model in the Glenn L. Martin wind tunnel.

This research was divided into two parts: formulation and analysis of bearingless rotors, and wind tunnel testing of an advanced bearingless rotor scaled model. The analysis was based on finite element theory in both space and time. A building block approach was used to advance the state-of-the-art on this topic. For test, a six foot diameter Froude-scaled four-bladed bearingless rotor model built by Boeing (under the ITR program) was acquired. To carry out the rotor stability test in the wind tunnel, a new rotor rig was built in house. The following research tasks were completed.

Six Foot Diameter Bearingless Rotor Model



3.1.1 Ground and Air Resonance Analysis of Bearingless Rotors in Hover

Ground and air resonance in hover was examined for a bearingless rotor using a finite element formulation. The blade configuration consisted of a single flexbeam with a wrap-around type torque tube with a vertical offset of the cuff snubber attachment point (Boeing-ITR Model). The blade, flexbeam and torque tube were all assumed to be elastic beams undergoing flap bending, lag bending, elastic twist and axial deflections, and these were discretized into beam finite elements. The fuselage was modeled as a rigid body undergoing five degrees of motion: longitudinal, lateral, and vertical translation, pitch angle, and roll angle.

Quasisteady strip theory was used to evaluate aerodynamic forces and unsteady aerodynamic effects were introduced approximately through an inflow dynamics model. Satisfactory correlation of predicted ground and air resonance results was carried out with data obtained from measurements on a 1/8th Froude-scaled dynamic model. Data were obtained by Boeing and this rotor model test was carried out in our Gl[illegible] Martin Wind Tunnel under ITR program. Systematic parametric studies were then carried out to examine the effects of several design parameters on ground and air resonance stability, including collective pitch, vertical offset of the inplane restraint of cuff snubber, hub precone, blade prepitch, blade sweep, pitch link stiffness, lag stiffness and rotational speed. Lag frequency showed a substantial influence on ground resonance stability, where as pitch-lag coupling (vertical location of cuff restraint), blade sweep and pitch link stiffness had powerful effects on air resonance stability.

3.1.2 Aeroelastic Stability Analysis of Bearingless Rotors in Forward Flight (Shaft-Fixed Condition) (Ph. D. Dissertation of Andrew L. Dull)

Aeroelastic stability characteristics for selected bearingless rotor configurations are calculated and correlated to experimental data. Bearingless rotors provide a simplified mechanical configuration since the flap, lag, and pitch bearings are all eliminated. However, the analysis of the bearingless blade is more involved because of the possible redundancy of load paths and non-linear coupling of the torsion and bending modes.

The rotor blade was analyzed by a finite element formulation based on Hamilton's principle. The beam element consisted of fifteen degrees of freedom in axial, bending and torsion deflections. Quasi-steady strip theory was used for the aerodynamic calculations while non-circulatory forces and dynamic inflow were included to approximate the unsteady effects. The analysis consisted of three stages: trim solution, blade steady response, and stability calculations. The trim solution was calculated for a simple rigid articulated blade for either wind tunnel or propulsive trim as the control input to the response calculations. The periodic response was calculated by a time finite element method after the non-linear finite element in space equations were transformed to normal mode equations using the first few vacuum rotating modes. Then the stability was calculated from the perturbation equations of motion linearized about the steady response solution. These equations were transformed with the first few coupled rotating modes and solved for stability by Floquet transition matrix theory.

The bearingless rotor analysis was correlated to hover lag mode stability data for a simple three-bladed rotor tested in three different pitch link configurations. The analysis was extended to forward flight although no experimental data were available in these cases. A second more complicated bearingless configuration which includes precone, blade twist, blade sweep, and a lag shear restraint was then analyzed and correlated to experimental data for both hover and forward flight. Parametric studies were presented showing the effect of pitch link stiffness, blade stiffness, sweep, precone, prepitch, thrust level, and lag pin position on blade stability in both hover and forward flight. The bearingless rotor program was flexible in analyzing rotor blades with a variety of physical constraints and the analytical results demonstrated good correlation to the experimental results in both hover and forward flight [Dull 88]

3.1.3 Air Resonance Analysis of Bearingless Rotors in Forward Flight

(Ph. D. Dissertation of Jinsoek Jang)

Air resonance of an advanced bearingless rotor in forward flight was examined using a finite element formulation in space and time. The blade configuration consisted of a single flexbeam and a wrap-around type torque tube with a vertical offset of the cuff snubber attachment point.

The analysis consisted of three phases: vehicle trim, steady rotor response, and stability of rotor/vehicle perturbation equations. Propulsive trim which simulates a free flight condition of the vehicle is used to calculate pilot controls and vehicle attitude. The solution was determined from vehicle overall equilibrium equations: three force (vertical, longitudinal, and lateral) and two moment (pitch and roll) equations. The steady rotor response involved the determination of time dependent blade position at different azimuth locations for one complete revolution. The flexbeam, torque tube and outboard blade were all assumed to be elastic beams undergoing flap bending, lag bending, elastic twist, and axial deflections. Each blade was discretized into a number of beam elements. To reduce computation time, the finite element equations were transformed into the modal space as a few normal mode equations using the coupled natural vibration characteristics of the blade. These nonlinear periodic coupled equations are then solved using a finite element in time procedure. To start the process, the vehicle trim and rotor steady response were calculated as uncoupled solutions, and then in subsequent iteration cycles, both these phases were calculated as one coupled solution using a modified Newton method. Therefore, overall vehicle force and moment equilibrium equations were always satisfied by a converged solution.

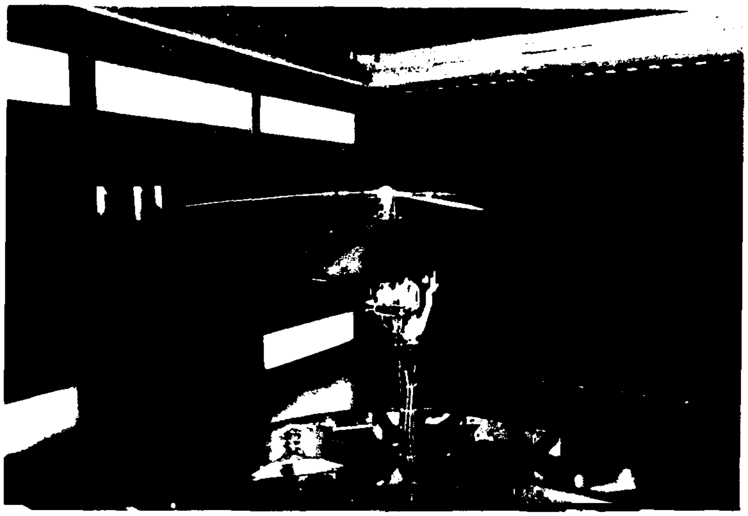
The third phase involved the determination of stability roots of the rotor/body perturbation equations in forward flight. The helicopter was assumed to be a rigid body undergoing three translational degrees of motion (vertical, longitudinal, and lateral) and two rotational degrees of motion (pitch and roll) about the body center of gravity. The blade perturbation equations about its steady deflected position were derived including five hub motions. The blade normal mode equations in the rotating frame, containing periodic terms were then transformed to the fixed frame using multi-blade coordinate transformation. Body equations of motion were derived in the fixed frame including rotor forces. The aerodynamic and inertial forces and moments acting on the blades were summed at the hub using multi-blade coordinate transformation to obtain rotor forces in the fixed frame. Unsteady aerodynamic effects were introduced in an approximate manner through a dynamic inflow modeling. The perturbation rotor, body and inflow equations in the fixed frame contained periodic terms and these were solved for stability roots using Floquet Transition Matrix Theory.

First, correlation of calculated stability results was carried out with the measured data obtained from an advanced bearingless rotor model tested by Boeing Helicopter Company at the University of Maryland's Glenn L. Martin wind tunnel. For this, the wind tunnel trim condition was simulated in calculations. Satisfactory correlation was observed between predicted and measured lag mode damping at different forward speeds. Then, parametric studies were undertaken to examine the effects of several design variables on air resonance stability of bearingless rotors, including vertical position of lag pin, hub precone, blade pretwist, blade sweep, pitch-link stiffness, dynamic inflow, and forward speed. It was shown that pitch-lag coupling (vertical location of cuff restraint), pitch-link stiffness, body roll inertia and blade precone have substantial effect on air resonance stability.

This task was presented at the Second International Conference on Rotorcraft Basic Research held in College Park, Maryland in February, 1988 [Jang 88a].

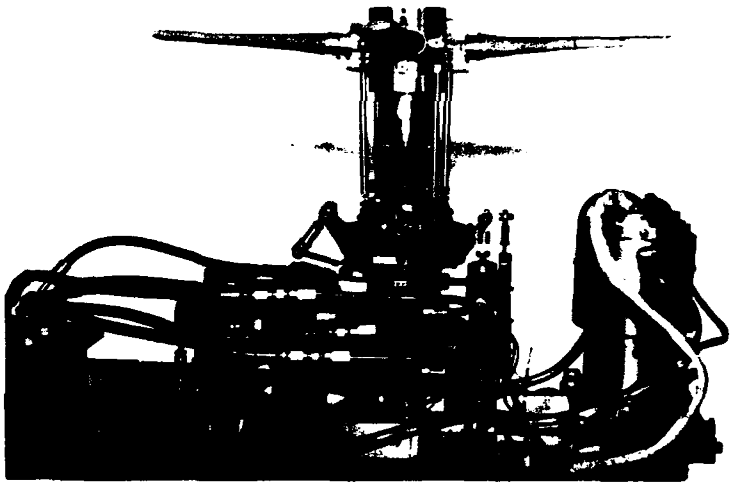
3.1.4 Aeroelastic Stability Testing of an Advanced Bearingless Rotor Model in the Glenn L. Martin Wind Tunnel (Shaft-Fixed)

An existing advanced bearingless rotor model was tested for aeroelastic stability in the Glenn L. Martin Wind Tunnel. The objective of this task was to provide a new and much needed data set on the stability of a bearingless rotor in hover and forward flight for the shaft-fixed condition, which can be used by researchers to validate their theories. Also, it was important to



Bearingless Rotor Model in the Glenn L. Martin Wind Tunnel 6 ft. diameter, Froude scaled

Bearingless rotor rig for stability testing, body pitch and roll motions about gimbal



Bearingless rotor hub

determine whether the present bearingless rotor system was stable from aeroelastic stability without the incorporation of auxiliary dampers. The rotor was fabricated by Boeing Helicopter Company under the ITR program. The rotor consisted of four blades, six feet in diameter and Froude-scaled. Each blade was attached to the hub through a single flexbeam with a wrap-around torque tube. One end of the torque tube was rigidly attached to the blade and the other end was pivoted at a vertical offset point as well as connected to the pitch link at the leading edge.

To test this rotor model in the Glenn L. Martin Wind Tunnel, a completely new model rig was designed and built. The new rig consisted of a shaft, a swashplate supported on three electro-hydraulic servo-actuators, a six component balance and a drive system. The shaft was driven by a 40 horsepower lightweight hydraulic motor through a belt-pulley arrangement. The entire assembly was suspended on a six component rotor balance. The balance itself was supported on a shaft pivot, and could be tilted by means of a hydraulic servo-actuator. This enabled us to achieve the desired shaft tilts ranging from -30° to +10°. The swashplate inclination was remotely controlled by the feedback potentiometers installed on the actuators. To excite the blades in rotating frame, the swashplate was excited dynamically using servo-actuators, up to a maximum frequency of 25 Hz.

Before stability testing, the blade static structural properties such as flap, lag, and torsion stiffnesses were measured. The stiffnesses were determined by statically loading each blade and then measuring the deflection using a laser system. Then, the shake tests were performed on each blade to determine its natural vibration characteristics. The rotor was tested both in hover as well as in forward flight in the Glenn L. Martin wind tunnel. The following test matrix was used:

Hover:

1) Nominal RPM (817); collective sweep in 2° increments (-2°, 0°, 2°, ... 10°)
2) RPM sweep (100 to 1000) in increments of 100 RPM at a moderate collective pitch of 2°

Forward Flight:

i) Collective sweep -2° to 10° at nominal rotor rpm, shaft-tilt sweep -15° to 5° in 2° increments
ii) Repeated above at various advance ratios up to 0.4 in 0.05 increments

The lag damping of the blade in forward flight was determined using the shake and decay method. The transient response data from the instrumented flexbeam was analyzed for frequency and damping of lag mode in rotating frame using an improved Moving-Block Analysis as well as newly developed Sparse Time Domain technique. The algorithms were executed online using an HP-1000 minicomputer. Also, steady hub loads including higher harmonics were determined for each test condition.

3.1.5 Correlation of Measured Stability Results of an Advanced Bearingless Rotor with Analytical Predictions (Shaft-Fixed)

Aeroelastic stability data obtained from the above model test of an advanced bearingless rotor in the Glenn L. Martin wind tunnel were analyzed to determine lag mode damping at different flight conditions. In the present task, the measured stability results were correlated with calculated results based on the theory developed earlier by Dull.

The rotor analysis was based on the finite element method in space and time. The rotor blade, flexbeam, and torque tube were all modeled as elastic beams undergoing flap bending, lag bending, elastic twist and axial deflections. Blade response was calculated using a finite element in time method. The wind tunnel trim was calculated by minimizing the longitudinal and lateral cyclic flap angles. The linearized periodic rotor perturbation equations in the nonrotating frame were solved for stability roots using Floquet Transition Matrix theory as well as constant coefficient approximation. The correlation was carried out for a wide range of rotor shaft tilts, advance ratios, and collective pitch settings, and for two different pitch link stiffnesses.

Based on this study, the following conclusions were drawn:

1. The analysis predicted the lag mode damping satisfactorily for θ_{75} between 5° and 10°. However, the quasi-steady linear aerodynamic modeling over-predicted the damping values for higher collective pitch settings. Results indicates an improved aerodynamic model may be needed to achieve better predictions at extreme collective pitch settings.

2. Both theory and experimental results demonstrated this particular bearingless main rotor design is stable at all RPM and collective pitch settings tested.

3. The effects of blade pitch link stiffness on aeroelastic stability was examined both experimentally and theoretically. Soft pitch links improved aeroelastic stability in hover and at low advance ratio. This is because of the increased pitch-lag coupling with soft pitch links. At high advance ratio, such as 0.47, the use of soft pitch links caused a destabilizing effect.

Results of above two tasks were presented at the AHS National Specialists Meeting on Rotorcraft Dynamics held in Arlington, Texas in November, 1989.

3.1.6 Ground and Air Resonance Testing of an Advanced Bearingless Rotor Model in the Glenn L. Martin Wind Tunnel (Shaft-Free Condition)

Initially the existing rotor drive system was built for the shaft-fixed condition and therefore, the body degrees of freedom were restrained. The rig was modified to incorporate a gimbal system for body pitch and roll degrees of motion. This gimbal system is based on the design used by NASA Langley V/STOL tunnel on their 2 meter rotor rig.

For this new model rig, the rotor shaft housing is attached to the mounting yoke by means of pin and bearing arrangement at the pitch pivot point. The pitch motion is restrained by means of pitch spring attached between the shaft housing and the rear end of the mounting yoke, and restrained in such a way that rolling motion of the mounting yoke relative to balance block is permitted through roll spring. The existing six component balance is installed in the gimbal balance block and the entire system is mounted on the mounting pedestal. To restrain large pitch and roll motions during the unstable conditions, mechanical stops are provided at the gimbal pivot points. The pitch and roll angles are measured using rotary potentiometers mounted at the gimbal pivot points. Mechanical dampers are also installed at the gimbal points using bell cranks and push-rod assemblies.

For ground resonance stability testing, stiff pitch and roll springs are used to simulate the stiffness characteristics of a typical landing gear system. For air resonance stability testing, stiff springs are replaced with soft pitch and roll springs to simulate the free body condition.

The rig has a grabbing mechanism that can grab the shaft. This is used for creating a shaft-fixed condition of the rotor. The mounting pedestal has a single degree of freedom pivot that allows the model pitch angle to be varied at angles up to $\pm$ 20 degrees to simulate the forward flight as well as rearward flight conditions. The tilt angle is controlled by an external hydraulic actuator attached to the rigid post. A 40 HP hydraulic motor drives the rotor through a belt transmission.

This new rig was tested in the Glenn L. Martin Wind Tunnel in March 1990. The test procedure involved trimming the rotor for each combination of shaft angle and collective pitch setting by adjusting the longitudinal and lateral cyclic to minimize the rotor longitudinal and lateral flapping. Then, the swash plate was cyclically oscillated at the regressing lag frequency for about one second with a maximum amplitude of one degree. Then, the excitation to swash plate was cut off and the transient response from all blades was recorded for ten seconds at a sampling frequency of 204.8 H_Z. The Moving-Block technique was used to estimate the lag mode damping from the transient response. The following test matrix was used.

Advance ratio m	0(hover), .12, .23, .35
Shaft angle a_S	0°, 4°, 6°, 8°, 10°
Collective pitch θ_c	0°, 2°, 4°, 6°, 8°, 10°
RPM	817

3.1.7 Correlation of Measured Ground/Air Resonance Stability Results of an Advanced Bearingless Rotor with Analytical Predictions (Shaft-free)

Ground/air resonance stability data obtained above for a bearingless rotor were analyzed and correlated with analytical predictions. For calculations, the blade was modeled as an elastic beam undergoing flap bending, lag bending, elastic twist, and axial deformation. Analysis is based on finite element approach in space and time. Experimentally determined properties of blades and body were used as an input to the analysis code. For results, wind tunnel trim solution was implemented. The following conclusions were drawn from this study:

1. The analysis predicted the lag mode damping satisfactorily for hover and forward flight.

2. Both theoretical and experimental results demonstrated that this bearingless rotor design was stable at all RPM and collective pitch settings tested.

3. The effects of hub motion on aeroelastic stability was examined both theoretically and experimentally. Shaft-free condition showed slightly higher damping.

Results of above two tasks were presented at the Sixteenth European Rotorcraft Forum in Glasgow, Scotland in September 1990.

3.1.8 Fabrication and Testing of a New Bearingless Rotor Model in the Glenn L. Martin Wind Tunnel for Aeromechanical Stability

During the last ground/air resonance stability test in the Glenn L. Martin wind tunnel, it was discovered that the rotoı had dissimilar blades. Stiffness and inertial characteristics were not identical for all blades. Also, due to extensive testing of this rotor, there were apparent cracks on one of the composite torque tubes. Furthermore, during the wind tunnel test, it was found that hydraulic tubes carrying fluid for the motor and servo-actuators were more stiff than expected and therefore, could not simulate the air resonance condition for the rotor-body system (i.e., low stiffness for pitch and roll springs). In this task, a new four-bladed bearingless rotor was built, the existing rotor rig was modified and then the model was tested in the wind tunnel for aeromechanical stability.

The design of the new bearingless rotor model was identical to the existing one (Boeing ITR model) and was built in house using composite fabrication technology. Rigid foam was cut to the desired airfoil shape, joined with glass-epoxy spar and covered with fiber-glass skin and then cured in the autoclave. Lead masses were placed in the foam at several locations to achieve desired cg positions.

Existing hydraulic motor for the rotor was replaced with a small-size light-weight electric motor of about 5 HP. This reduced considerably the size of hydraulic tubes needed to convey fluid, only to three hydraulic servo-actuators. This in turn reduced the stiffness of hydraulic tubes and connectors during the wind tunnel test.

Extensive static and vibration tests were performed on all blades to check whether desired inertial and stiffness properties were simulated. More than four blades were built and tested for static characteristics to select the best ones with identical properties for testing in the wind tunnel. Then systematic aeromechanical stability tests on the complete rotor-body system were carried out, first for hovering condition, and later on, for forward flight condition in the Glenn L. Martin wind tunnel. This test was carried out in August 1991. For investigation of ground resonance stability, stiff pitch and roll springs were used, and for air resonance stability, soft pitch and roll springs were incorporated.

Measured transient data were analyzed using Moving-Block method as well as Sparse Time Domain technique to obtain damping of different modes. Half way during the test, lag gages on two of the blades failed. Though the complete test matrix was completed, however complete stability results were not available. Recently, blades were instrumented with new gages and hover testing on a hover stand was carried out. After the completion of testing on the hover stand, this rotor model will be tested in the Glenn L. Martin Wind Tunnel for aeromechanical stability.

Results from this Task were presented at the Fourth Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems held at the University of Maryland in November 1991.

3.1.9 Refined Modeling of Bearingless Rotor

An improved formulation for the bearingless rotor is developed to capture more realistically the associated complex kinematics and to improve the trim and stability analyses. These refined modeling and analysis features have been fully integrated in the UMARC (University of Maryland Advanced Rotorcraft Code). The current formulation is also quite comprehensive in nature; it can readily model various bearingless rotor design configurations cited in literature. These design configurations are characterized by inclusion/exclusion of shear lag restraint, inclusion/exclusion of a snubber with 6-dof stiffness and damping characteristics placed between the cuff and the flexbeam, number of flexbeams, and placement of the pitch horn relative to the blade. The major structural load-carrying members of the bearingless rotor, viz. the blade, the torque tube and the flexbeams, are idealized as Euler-Bernoulli elastic beams undergoing flap bending, lag bending, elastic twist and axial deflection. The inclusion of axial degree of freedom becomes essential for a multiple-load-path bearingless rotor configuration to properly model the flexure components. Each elastic beam member is discretized into a number of beam elements. The pitch link can be modeled either as a rigid element or as a linear spring element to simulate the control stiffness. The pitch horn, joining the pitch link to the torque tube, has both radial and chordwise offsets. The rotor can have hub precone, prepitch of the blade relative to the flexure, variable sweep and variable blade twist.

Presented below are results from a validation study on a simple bearingless rotor configuration (without any shear restraint pin or snubber) experimentally tested by Dawson in hover. Two cases of pitch control configurations are considered in the correlation study. The first case has a single pitch link at the leading edge and the second one has a pitch link at the trailing edge. Aeroelastic stability results are presented in terms of the blade damping plotted against the blade pitch setting.
For Case 1, the agreement between the data and the experimental values is good over the blade pitch range of -2^{o} to 4^{o}. The predicted damping value is minimum at blade pitch of 0.7^{o}, whereas the data shows that this occurs at an angle just below 2^{o}. For Case 2, analysis overpredicts lag damping at negative pitch settings and underpredicts it at positive pitch settings. Analysis also

predicts pich-flap flutter over blade pitch range of -4° to 4° This range is wider than the experimentally observed range of 0° to 2°.

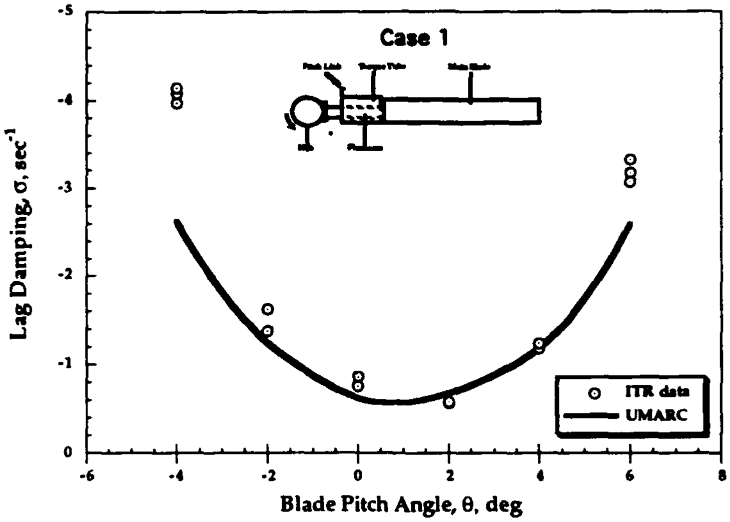


Figure 1: Aeroelastic stability of bearingless blade in configuration 1

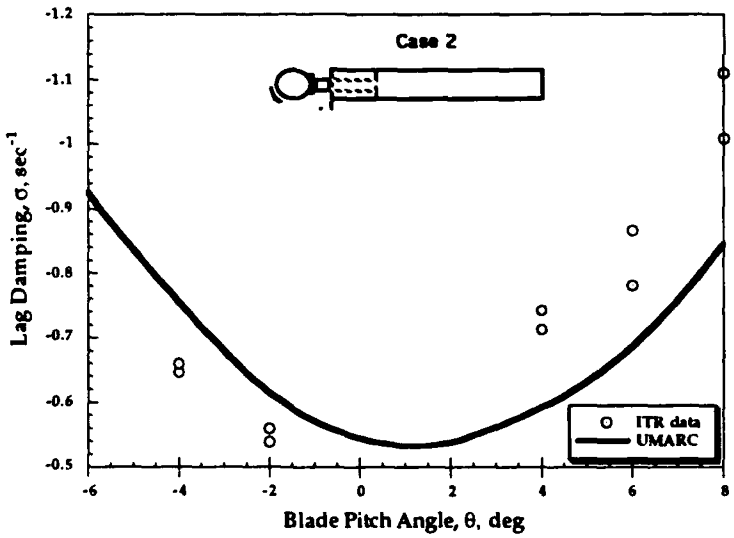


Figure 2: Aeroelastic stability of bearingless blade in configuration 2

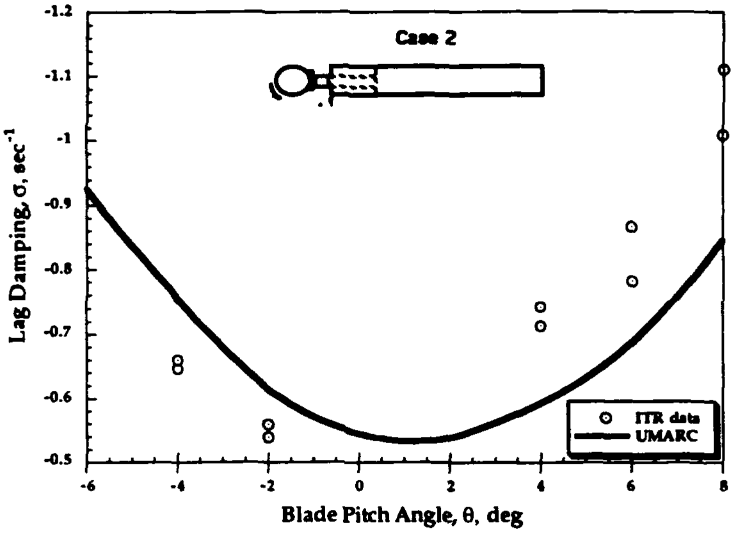


Figure 3: Aeroelastic stability of bearingless blade in configuration 2

3.1.10 Damping Estimation in Helicopter Rotor Stability Testing

(Ph. D. Dissertation of Frederick A. Tasker, 1990)

Estimating the damping of helicopter rotor blade modes is complicated by rotor harmonics, high measurement noise, close modes and the difficulty of exciting modes in the rotating environment. Methods are developed and evaluated for obtaining improved estimates of modal damping from rotor stability test data. Two transient analysis methods, Moving-Block analysis and the Sparse Time Domain (STD) method are studied. two refinements in Moving-Block analysis are introduced: High resolution recursive spectral analysis and a recursive frequency domain interpretation for the Hanning window to reduce leakage from close modes. Singular Value Decomposition is applied to the STD method and a procedure to calculate only the structural modes from the system matrix is developed. The techniques are evaluated for noisy data, close damped and undamped modes, for low and high damping levels. Moving-Block analysis is quite effective in estimating the damping of a mode from noisy data, whereas the STD method is very effective in estimating the damping of close modes. Some sample damping results were also calculated from experimental data obtained from a wind tunnel stability test on a model bearingless rotor.

Subspace methods substantially improve the time domain estimation for noisy data, but require higher computation time. A method is developed that retains the low variance estimation property of the subspace methods, but is comparable in computation cost to baseline methods. Its performance is evaluated for multi-output and single output implementations and compared to the standard STD method. It is found that the modified method is more accurate in terms of the bias and standard deviation of the damping estimates, and faster when the number of modes is much less than the order of the data matrix.

Equivalent Damping is estimated using modified versions of the Moving-Block analysis technique and the STD method from numerical simulations. Effects of rotor harmonics and noise on the performance of these techniques are evaluated. It was concluded that equivalent damping characteristics may be identified from sampled, multi-mode and noisy nonlinear transient response data using modified versions of the Moving-Block analysis and Sparse Time Domain technique.

3.2 DYNAMICS OF COMPOSITE ROTORS

Advanced composites are poised to meet many challenging requirements for future helicopters, and the rotorcraft industry is moving vigorously to apply this technology in the construction of rotor and airframe structures. All new rotorcraft including the Army's RAH-66 (Comanche) are being built extensively out of advanced composites. At this time, the potential benefits of composites are not fully exploited by the industry and an extreme level of conservatism is used in the design. One major reason is the lack of full understanding of the influence of structural couplings caused by composites on the dynamics of rotors.

Maryland carried out the very first studies on the dynamics of composite rotors showing the potential of structural couplings for improving vibration, lowering blade stresses and increasing aeroelastic stability. Since then, there have been numerous investigations by other researchers, directed primarily toward predicting the cross-sectional properties of composite beams. At Maryland, the research activities have covered from new and improved modeling, fabrication and testing of tailored models and validation of theories. Formulations for thin-walled composite beams were developed using simple analytical approaches and detailed finite element methods. Tailored thin-walled box beams, I-beams and multi-cell blades (airfoils) were built of graphite/epoxy and kevlar/epoxy plies and tested under static bending, torsion and extensional loads, and also under dynamic loading in our 10-ft. diameter vacuum chamber. These studies, in addition to improving our basic understanding of the structural behavior of composite blades, also perfected our skills in the fabrication of tailored composite blades.

Recently, Smith conducted a systematic aeroelastic study of a composite rotor in forward flight using a refined composite blade model. A new finite element-based composite analysis that included nonclassical effects was integrated into UMARC. Again, it showed the powerful influence of composite structural couplings on blade dynamics.

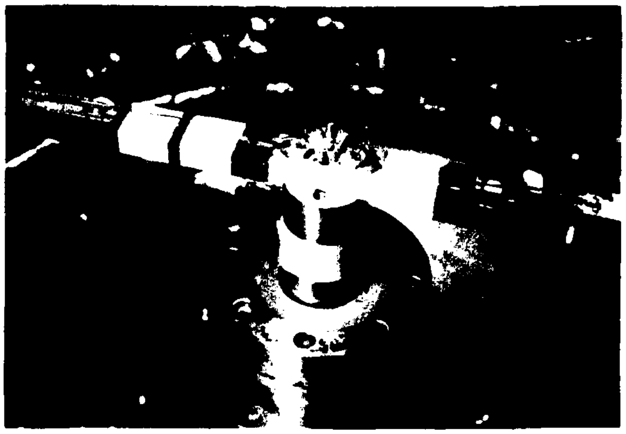
This research can be divided into two parts: modeling and validation of thin-walled coupled composite beams, and formulation and aeroelastic analysis of composite rotors.

3.2.1 Thin-Walled Composite Beams Under Bending, Torsional and Extensional Loads

Symmetric and antisymmetric graphite-epoxy composite beams with thin-walled rectangular cross-sections were fabricated using autclave molding technique and tested under bending, torsional and extensional loads. The bending slope and elastic twist at a station were measured using an optical system. The measured bending slope and twist distributions were correlated with predicted results obtained using a simple beam analysis as well as a refined finite element analysis. A symmetric lay-up results in bending-twist coupling whereas an antisymmetric lay-up causes extension-twist coupling. Simple analytical results with plane-stress assumption agreed better with measured data as well as finite element predictions than with plane-strain assumption. For symmetric layup beams, the bending-induced twist and torsion-induced bending slope were predicted satisfactorily using analytical model. Correlation with measured data, however, were generally improved using a finite element solution. For antisymmetric layup beams, axial force-induced twist was predicted satisfactorily by both methods. Cross-sectional warping and transverse shear were shown to have substantial influence on the structural response of symmetric and antisymmetric beams.

3.2.2 Experimental-Theoretical Investigation of Vibration Characteristics of Rotating Composite Box Beams

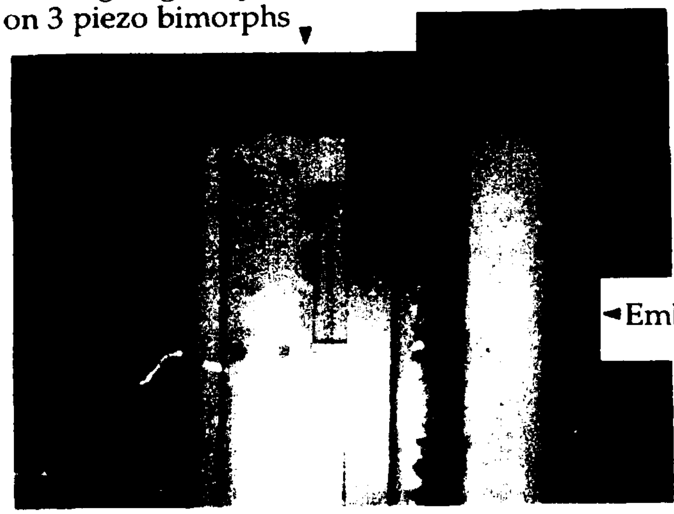
This paper presented a theoretical-cum-experimental study of the free vibration characteristics of thin-walled composite box beams with bending-twist and extension-twist coupling under rotating conditions. The governing equations in generalized displacements were derived using a Newtonian approach. The composite structural model in the derivation used a solid-section approach and contained transverse shear-related couplings and appropriate cross-section warping. The free vibration characteristics of composite box beams were determined by the Galerkin method. In order to validate the theory, glass-epoxy, kevlar-epoxy and graphite-epoxy symmetric and antisymmetric box beams were fabricated using an autoclave molding



2-Bladed rotor in vacuum chamber, excitation and sensing using piezoelectric crystals

Vacuum chamber: 10ft. diameter, 1 milibar vacuum, 100 channels slip-ring, RPM up to 1000

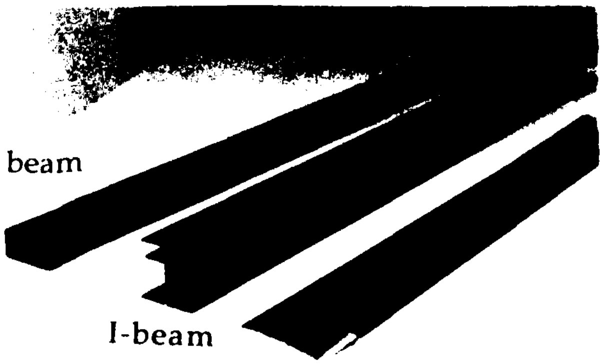
Trailing edge flap mounted on 3 piezo bimorphs



Embedded piezo crystals at ±45°

Smart structure rotor blades

Beams and Blade built out of graphite-epoxy using autoclave molding technique, length 30 in.



Box beam

I-beam

2-Cell Blade

technique, and tested in an in-vacuo rotor test facility for their vibration characteristics. Beam excitation in the rotating condition was effected by means of induced-strain actuation with the help of piezoceramic bending elements. Strain gages were used to measure the response of the first three modes over a range of rotational speeds up to 1000 RPM. It was determined that the experimental frequencies and mode shapes correlated satisfactorily with the theoretical results. It was shown that bending-shear coupling influenced the flexural vibration frequencies of antisymmetric box beams significantly. Extension-shear coupling, on the other hand, did not influence the flexural-torsion vibration frequencies of symmetric box beams significantly.

3.2.3 Formulation and Evaluation of an Analytical Model for Composite Box-Beams

A direct analytical beam formulation was developed for predicting the effective elastic-stiffnesses and corresponding load deformation behavior of tailored composite box-beams. Deformation of the beam was described by extension, bending, torsion, transverse shearing, and torsion-related warping. Evaluation and validation of the analysis were conducted by correlation with both experimental results and detailed finite element solutions. The analysis was evaluated for thin-walled composite beams with no elastic coupling, designs with varying degrees of extension-torsion and bending-shear couplings, and designs with bending-torsion and extension-shear coupling. The analysis was performed well over a wide range of test cases, generally predicting beam deformations within 10 percent of detailed finite element solutions. The importance of three non-classical structural phenomena was systematically investigated for coupled composite beams. Torsion-related warping can substantially influence torsion and coupled torsion deformations; twist of a symmetric layup box-beam under a tip bending load can increase up to 200 percent due to warping. Couplings associated with transverse shear deformations can significantly alter the elastic response of tailored composite box-beams; effective bending stiffness of highly coupled anti-symmetric layup beams can be reduced more than 30 percent. Two-dimensional elasticity of the plies is also very important to the accuracy of composite box-beam analysis; load deflection results for anti-symmetric layup beams can be altered by 30-100 percent by not accounting for this elastic behavior.

3.2.4 Experimental and Theoretical Analysis of Composite I-Beams with Elastic Couplings

This paper presented a theoretical-cum-experimental study on the static structural response of composite I-beams with elastic couplings. A Vlasov-type linear theory was developed to analyze composite open section beams made out of general composite laminates, where the transverse shear deformation of the beam cross section was included. The essence of this theory is the reduction of two-dimensional stress and displacement fields to one-dimensional beam forces and displacements. In order to validate this analysis, graphite-epoxy and Kevlar-epoxy symmetric I-beams were fabricated using an autoclave molding technique. The beams were tested under tip bending and torsional loads, and their structural response in terms of bending slope and twist was measured with a laser optical system. Good correlation between theoretical and experimental results is achieved. A 630% increase in the torsional stiffness due to constrained warping is noticed for graphite-epoxy beams with slenderness ratio of 30. Also extension-twist coupling "B_{16}" of flanges of these I-beams increases the bending-torsion coupling stiffness of beams manyfold.

3.2.5 Vibration Characteristics of Composite I-Beams with Elastic Couplings Under Rotation

This paper presents a free vibration analysis of composite I-beams with couplings under rotating environments. A linear analysis based upon Vlasov theory was developed to obtain coupled flap-lag-torsion equations of motion for I-beams made out of general composite laminates. Constrained warping and transverse shear effects were included. These equations were solved using Galerkin's method. Significant influence of constrained warping and bending-torsion coupling on natural frequencies was observed. In order to provide a selective validation of the theory, graphite-epoxy and kevlar-epoxy symmetric I-beams were fabricated using an autoclave molding technique and tested in an in-vacuo rotor test facility for their vibration characteristics. Induced-strain actuation with the help of piezo-ceramic elements was used to excite the rotating I-beams. Strain gages were used to measure the response of these beams over a range of rotational speeds up to 1000 RPM. Good correlation between theory and experiment was achieved. A 1200 percent increase in torsional frequency due to constrained warping occurs for graphite-epoxy beams with slenderness ratio of 18.

3.2.6 Structural Response of Multi-Cell Composite Rotor Blades with Elastic Couplings

This paper presents an analytical-cum-experimental study of the structural response of composite rotor blades with elastic couplings. Vlasov theory was expanded to analyze two-cell composite rotor blades made out of general composite laminates including the transverse shear deformation of the cross-section. Variation of shear stiffness along the contour of the section was included in the warping function. In order to validate this analysis, two-cell graphite-epoxy composite blades with bending-torsion and extension-torsion couplings were fabricated using matched-die molding technique. These blades were tested under tip bending and torsional loads, and their structural response in terms of bending slope and twist was measured with a laser optical system. Good correlation between theory and experiment was achieved. The slenderness ratio of the blade controls the difference in single-cell and two-cell predictions. For bending-torsion coupled blades with a slenderness ratio of 36, single cell approximation overestimated the bending and torsional flexibilities by 87% and 41% respectively. Axial force induced twist rate of the order of 0.2 degree per inch length can be realized in extension-torsion coupled blades with a hygrothermally stable $[20/-70]_{2S}$ layup for potential applications in the design of tilt rotors.

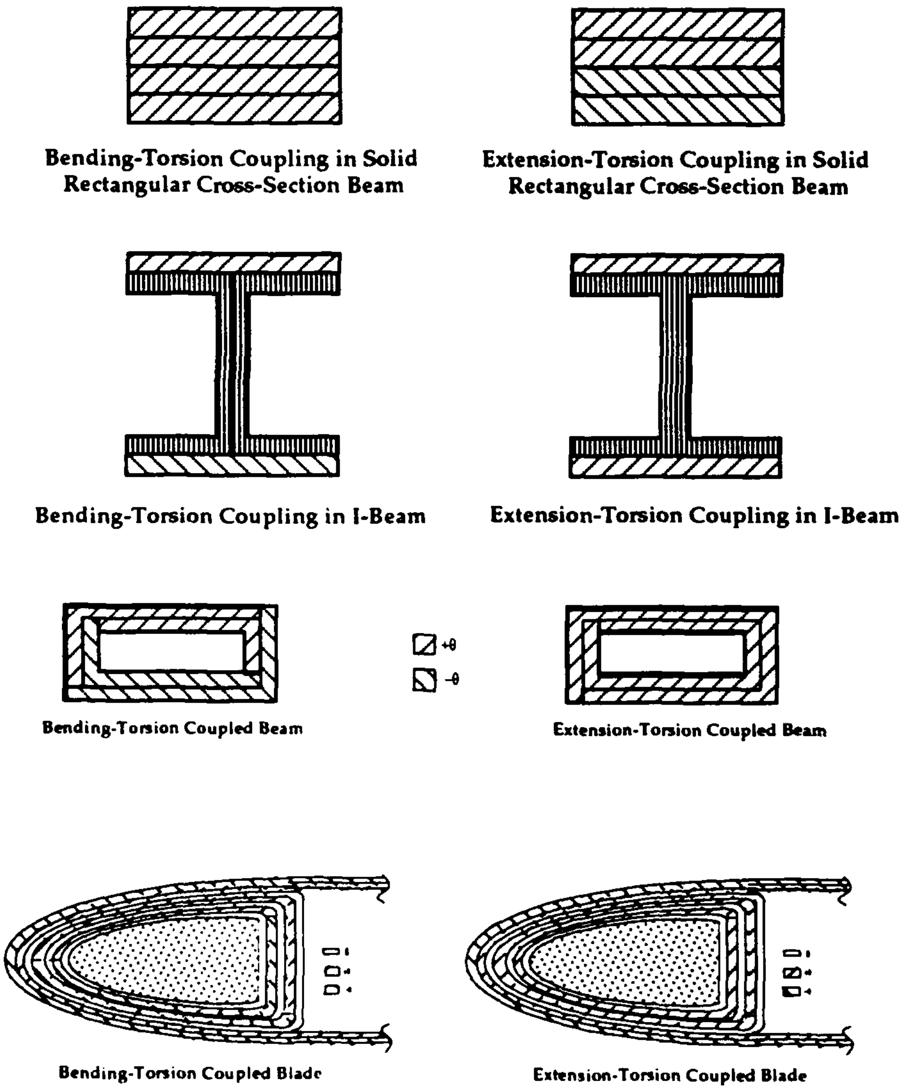


Figure 1: Lay-up details for coupled composite beams

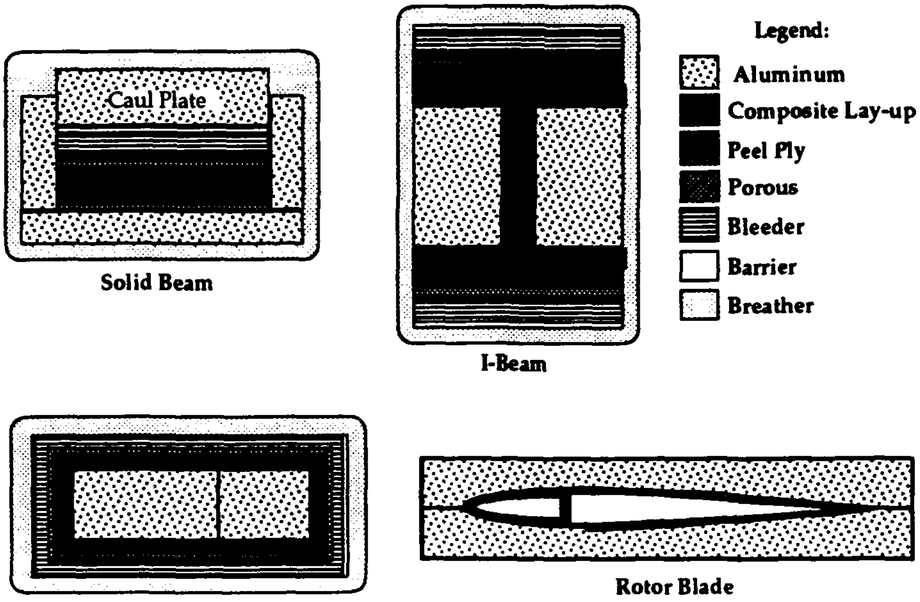


Figure 2: Details of composite beam fabrication

3.2.7 Structural Modeling of Composite Beams with Induced-Strain Actuation

This paper presents an analytical-experimental investigation on structural modeling of coupled composite beams with distributed induced-strain actuators. Analysis based on Vlasov theory is developed to include distributed piezoelectric actuators, either surface mounted or embedded. In order to evaluate the analytical predictions, several bending-torsion and extension-torsion coupled graphite-epoxy solid beams were fabricated using an autoclave molding technique. These were surface mounted with piezoelectric actuators. The actuators were excited to produce local bending moments and axial force on the beam and the structural response was measured in terms of bending slope, induced twist and surface strain. Good correlation between analysis and experiment was achieved. Due to the existence of a chordwise actuator moment, the twisting of bending-torsion coupled beams was significantly influenced by including the chordwise curvature of the plate segment of beam in the formulation. For $[45]_{24}$ solid beams, the chordwise bending of the plate segment of beam was found to increase the tip twist by about 100%.

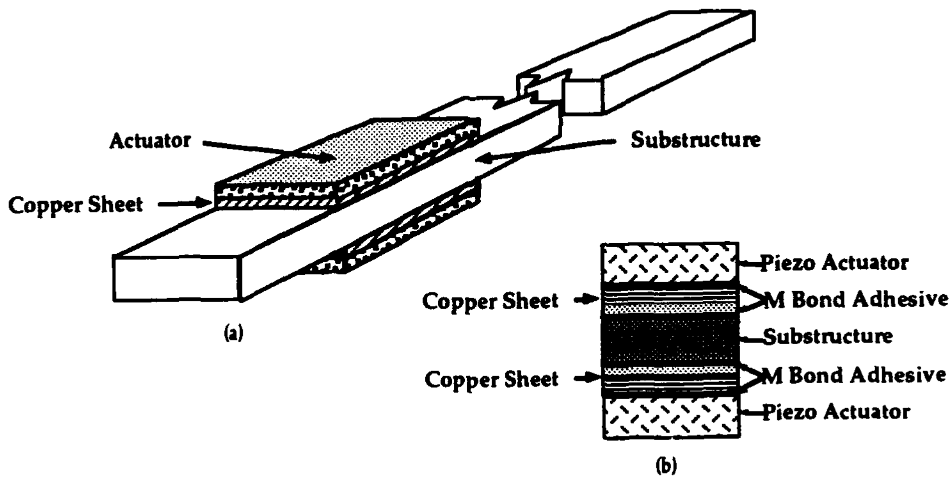


Figure 1: Solid beam with piezo actuator

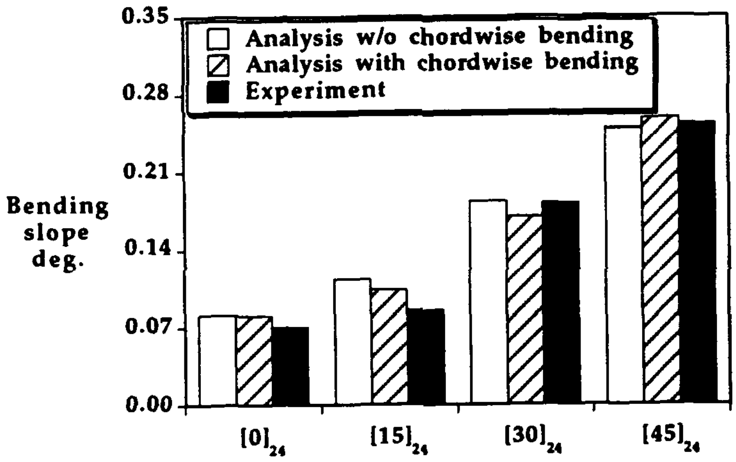


Figure 2: Bending slope of solid beams with piezo actuator

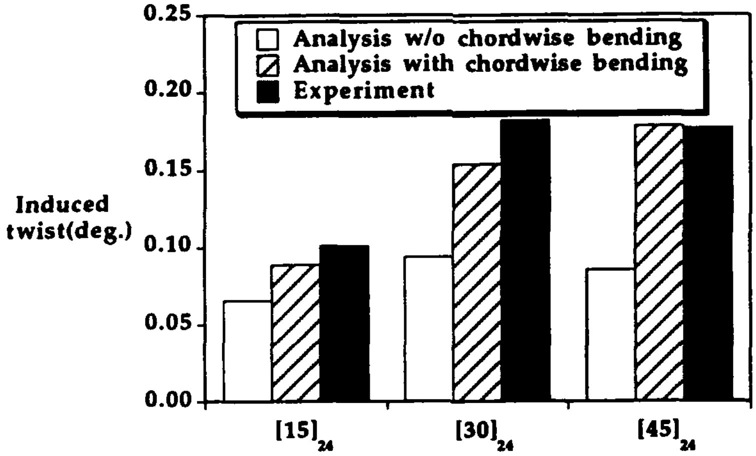


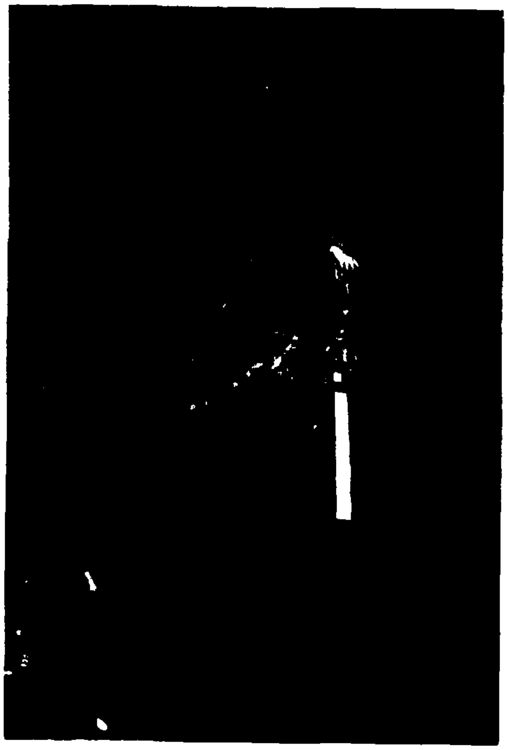
Figure 3: Bending slope of solid beams with piezo actuator

3.2.8 Aeroelastic Response and Aeromechanical Stability of Helicopters with Elastically Coupled Composite Rotor Blades

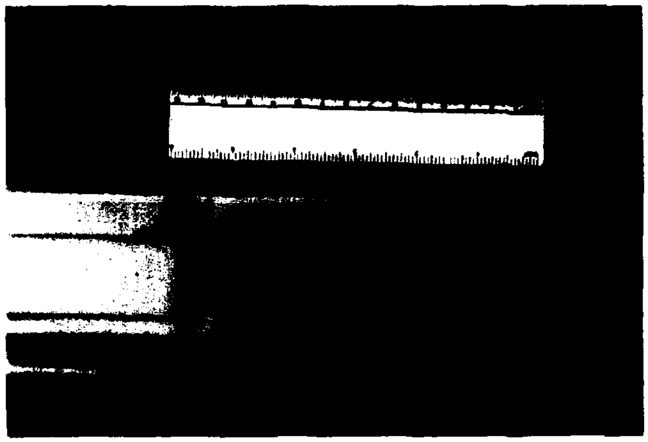
(Ph. D. Dissertation of Edward C. Smith, 1992)

A comprehensive formulation has been developed to study the effects of elastically coupled composite helicopter rotor blades on aeroelastic response, blade and hub loads, rotor aeroelastic stability, and rotor-fuselage aeromechanical stability. Both hover and forward flight conditions are addressed and the aeromechanical stability analysis includes both air and ground resonance phenomenon. A new analysis has been formulated to model the laminated composite box-beam blade spar. The box-beam analysis, based on classical lamination theory, includes the nonclassical structural effects of transverse shear, torsion-related out-of-plane warping, and two-dimensional ply elasticity. Elastic couplings such as pitch-flap, pitch-lag, and extension-torsion are introduced through the anisotropy of the plies in the composite spar. For the aeroelastic and aeromechanical analysis, the blade is idealized as an elastic beam undergoing moderate deflections in flap and lag bending, elastic torsion, elastic axial deformation, and flap and lag transverse shear. A nineteen degree of freedom shear flexible beam element is introduced for the composite rotor blades. The structural model is validated by correlation with experimental data and finite element solutions for static deflections of elastically coupled graphite-epoxy composite box-beams. The quantitative importance of the nonclassical structural effects is also investigated. The free vibration analysis is validated by correlation with experimental data and finite element results for the in vacuo rotating natural frequencies of the composite box-beams. The aeromechanical stability analysis is correlated against experimental data for a model hingeless rotor-

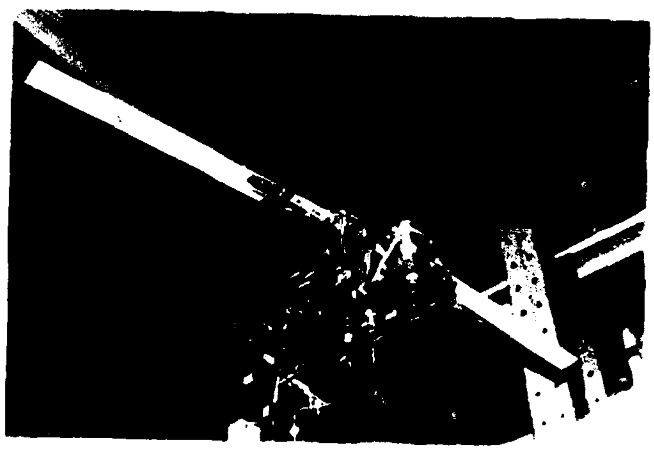
Different types of rotor blades; standard, embedded piezo-ceramics for twisting, embedded piezo-ceramics for bending, and trailing-edge flap mounted on bimorphs



2-Bladed bearingless rotor (6 ft dia) on hover stand, 10% flap mounted on 3 piezo bimorphs



Trailing-edge flap mounted on 3 piezoelectric bimorphs



2-Bladed bearingless rotor (6 ft dia) on hover stand, controllable twist-camber blades

body configuration. Using the new aeroelastic and aeromechanical analysis, rotors with five different composite spar layups are examined; a baseline composite blade with no ply-induced elastic couplings, three symmetric layup composite blades featuring negative pitch-flap elastic coupling, positive pitch-flap elastic coupling, and negative pitch-lag elastic coupling, and an anti-symmetric layup blade featuring extension-torsion and bending-shear elastic couplings. Results indicate that elastic couplings introduced through the composite blade spar have a powerful effect on both shaft-fixed blade stability and rotor-body aeromechanical stability. The torsional response is also significantly affected by the composite couplings. Influence of composite couplings on blade and hub loads was measurable, but less pronounced. See Refs [93a, 93b]

3.2.9 Aeromechanical Stability of a Bearingless Composite Rotor in Forward Flight

With the application of composite materials, many advanced rotor systems are becoming feasible today. These advanced rotor systems include hingelesss and bearingless rotors. A bearingless configuration is a specialized case of a hingeless rotor, where the pitch bearing as well as the flap and lag hinges are eliminated. A typical bearingless configuration is shown in Figure below. Advanced rotor configurations offer mechanical design simplicity (fewer parts), more control power, and better maintainability. Due to blade stress and weight considerations, these rotors are typically designed as soft in-plane rotors. This makes them susceptible to aeromechanical instabilities such as air and ground resonance. The objective of this research task is to: 1) formulate a refined aeroelastic analysis of a bearingless rotor and 2) examine the influence of composite couplings on its dynamics in hover and forward flight.

The first phase is to develop a refined formulation to obtain section properties of a composite blade involving open as well as closed section thin-walled members. The flexbeam is modeled as a composite thin-walled open section beam, such as an I-beam, while the main blade is modeled as a composite box beam. Important non-classical effects such as cross-section warping, constrained warping, and transverse shear are included. The modeling of thin-walled structural members is based upon the modified Vlasov theory developed by Chandra and Chopra. The walls of individual beam members are modeled as generalized composite laminates. Development of theory involves reducing the two-dimensional stress and displacement field of the laminates to a one-dimensional generalized force and displacement field of the beam.

The second phase involves the development of aeroelastic analysis of a bearingless rotor. A new finite element based structural analysis including the effects of transverse shear and warping restraint is incorporated into the UMRAC (University of Maryland Advanced Rotorcraft Code). The effects of transverse shear are implicitly included through static condensation of the shear degrees of motion. The effects of restrained warping are incorporated approximately by modifying the torsional stiffness distributions along the blade. For this phase of analysis, the reduced structural characteristics obtained in the first phase are used as input to calculate blade response and rotor-body stability.

The next phase is to apply the new analysis to an advanced composite bearingless rotor. Three soft inplane bearingless rotor configurations, including bending-torsion and extension-torsion couplings are analyzed. The analysis covers free flight propulsive trim, blade steady periodic response, and stability of perturbed rotor-body system. Elastic pitch-lag couplings caused by the ply layup of the flexbeam have a significant effect on the vibratory response, hub loads, and aeroelastic stability of a bearingless rotor. Negative pitch-lag coupling has a stabilizing effect on the lag mode stability in both hover and forward flight.

3.3 GUST RESPONSE OF HINGELESS ROTORS

Gust response of a helicopter is important as it not only influences ride quality but also contributes to structural fatigue. Its understanding is required in the development of gust alleviation devices. Gust response studies have acquired more significance recently because rotor designs are tending towards hingeless and bearingless configurations, which have higher dynamic stresses and vibration levels. Additionally, Army tactics call for the military helicopter of the future to spend much of its operational life in the highly turbulent atmosphere in the "nap of the earth" (NOE), (i.e., at and below the tree line). Therefore, it becomes necessary to develop accurate analysis to predict response of a combined rotor-body system to generalized atmospheric turbulence, both deterministic and random. At Maryland, Bir formulated a comprehensive analysis to calculate rotor-body response due to *deterministic* gusts of arbitrary orientation and time history over a wide range of advance ratios. The present research is directed to study the helicopter response due to non-deterministic gust.

3.3.1 Helicopter Response to Atmospheric Turbulence in Forward Flight

(Ph. D. Dissertation of Andrew S. Elliott 1987)

The deterministic and random gust response of a helicopter in forward flight is examined analytically, using a state space formulation in the time domain. The gust response is considered to be a perturbation about the steadily periodic solution. The hingeless rotor blades are modelled structurally as rotating elastic beams undergoing out-of-plane bending. The blades are discretized using the finite element method and the equations of motion are transformed into a modal space using the first few normal modes. The rotor hub and fuselage are considered as a rigid body with a single degree of freedom along the shaft axis. The aerodynamic forcing is developed from a two-dimensional unsteady time domain model based on an exponential series approximation for the response to an indicial change in the downwash. Compressibility effects are included. This model is converted to an equivalent state space representation at radial stations along each blade and these states are appended to the state vector. For computation of the steadily periodic rotor response, the aerodynamic model is extended to include separation effects and dynamic stall. The external environment consists of a uniform free stream velocity, plus either a one-dimensional deterministic gust, or a one-dimensional, nonstationary, Gaussian stochastic perturbation with known mean and standard deviation. This perturbation has von Karman power spectral density distribution, which is approximated by adding a first order shaping filter to the system, forced by white noise. The statistically sufficient characteristics of the random response, namely the mean vector and covariance matrix, are obtained by direct time integration of a first order matrix state equation. Threshold crossing and peak value statistics are derived for any arbitrary threshold level. Results are presented for a representative helicopter flying at various combinations of advance ratio, turbulence intensity and scale length typical of low altitude and nap-of-the-earth flight environments. These include deterministic and statistical blade loads, deflections and hub motions. Inclusion of an appropriate unsteady model for the aerodynamic forcing is shown to be essential to accurate response prediction at high advance ratios.

3.4 MODELING OF ROTOR UNSTEADY AERODYNAMICS

The aerodynamic flow field on a rotor disk is very complex and is coupled with blade motion. The blade encounters transonic flow with shock waves at its advancing blade tip, speed reversal and stalled flows at its retreating side, and swept flows on its fore and aft positions. Currently, most of the rotorcraft codes developed to predict aeroelastic response in forward flight employ relatively simple aerodynamic models. A quasi-steady two-dimensional (2D) aerodyanmic approximation is commonly used, and airfoil characteristics are expressed in the form of analytical expressions or tabular data. In such approaches, unsteady aerodynamic effects are represented in an approximate manner and the influence of transonic flow on the advancing side is typically neglected. In practice, a higher level of sophistication is structural modeling is used than that for aerodyanmic modeling. On the other hand, more detailed computational methods for rotary-wing aerodynamics are available. One of the major reasons for inhibiting their general use is the computational time requirement associated with a coupled code based on comparable sophistication in both structural and aerodynamic models.

The objective of this research was to improve the aerodyanmic modeling in coupled rotor aeroelastic analysis to calculate oscillatory hub loads, blade bending and aeromechanical stability. Two type of unsteady aerodyanmic models are investigated; nonlinear time-domain unsteady aerodynamics including dynamic stall and detailed small-disturbance finite-difference transonic aerodynamics.

3.4.1 Rotor Loads and Stability Analysis using Non-linear Unsteady Aerodynamics

(Ph. D. Dissertation of Michael S. Torok, 1989)

The effects of improved aerodynamic modeling on rotor blade section and hub loads, blade response, and blade stability were investigated. A non-linear unsteady aerodynamic model for attached and separated flow and dynamic stall, as well as prescribed and free wake models, were incorporated into a coupled rotor aeroelastic analysis. Blade responses and loadings were calculated using a finite element formulation in space and time. A modified Newton iterative method was used to calculate blade response and trim controls as one coupled solution. Aeroelastic stability was determined utilizing Floquet theory for a linearized system, and a transient perturbation technique which can model non-linear unsteady aerodynamic effects. Damping estimations were made using a Moving-Block analysis. Results of a parametric study of a soft in-plane hingeless rotor showed that at high speed flight conditions, non-linear effects dominate blade section forces, and significantly affect peak-to-peak values and the harmonic content of blade root loads. These effects were amplified at higher thrust conditions. Compressibility effects and blade twist considerably influenced the extent of separated flow on the rotor disk. Free and prescribed wakes gave similar results at a high speed flight condition. A correlation with SA349/2 Aerospatiale Gazelle flight test data was used to evaluate the analysis. Trim controls, blade section aerodynamic loads, and blade flap bending moments were satisfactorily predicted. The non-linear aerodynamic model improved correlations in a high speed, high thrust, flight condition. The free wake analysis was important for capturing the harmonics of flap bending moments and low advance ratio, aerodynamic blade section loads. The rotor stability analysis was correlated with model hingeless rotor data. At high advance ratios, the inclusion of unsteady aerodynamics in the damping predictions significantly improved correlation. Dynamic inflow yielded only minor improvement in damping correlation. A parametric study of a hingeless rotor in forward flight was examined. Both dynamic inflow and unsteady aerodynamics significantly influenced predicted lag mode damping. Compressibility effects exhibited only small influence on lag damping. Flow separation and dynamic stall were important factors in the transient response of a rotor in high thrust flight conditions.

3.4.2 Dynamic Analysis of Advanced Tip Rotors Including Three Dimensional Aerodynamics

(Ph. D. Dissertation of Ki Chung Kim, 1990)

A systematic investigation of the effects of tip sweep, anhedral and planform taper on helicopter rotor blade response and loads was conducted using comprehensive structural and aerodynamic models. A finite element method was used for the structural analysis, and a three-dimensional (3D) finite difference aerodynamic analysis, based on unsteady transonic small disturbance theory (TSD), was used to calculate the aerodynamic loads. The blade and its tip were treated as elastic beams undergoing flap bending, lag bending, elastic twist and axial deflections. Nonlinear transformation relations based on moderate rotations were used to assemble the blade and tip elements. The blade response was calculated from nonlinear periodic normal mode equations using a finite element in time scheme. To represent the inflow distributions through the rotor disk, a free wake model was used. Dynamic stall and reverse flow effects were also included. Vehicle trim and rotor elastic response were calculated as one coupled solution using Newton's method. The blade steady response, rotor controls and blade loads were recalculated using the three dimensional lift and moment obtained from the TSD analysis. An iterative coupling scheme was developed for efficient coupling between the aeroelastic and 3D finite difference codes. Calculated results were correlated satisfactorily with flight test data obtained from the Gazelle helicopter (with a straight-tip blade) for several level flight conditions. Results were then calculated for this rotor with advanced tip shapes and the effects of 3D aerodynamics were assessed. For a high forward speed condition (μ = .378), there was a considerable influence of 3D aerodynamics on blade response and loads and the correlation of aerodynamic loads was improved with the inclusion of 3D aerodynamics, particularly near the outboard section of the blade. Inclusion of 3D effects in pitching moment appeared quite large and helped to improve the correlation for torsional moment in the high speed case. Tip sweep introduced a kinematic axial-lag coupling induced by the centrifugal force. Three dimensional aerodynamic effects of lift distributions and bending moment variations were quite considerable for both swept-tip and anhedral-tip blades.

3.4.3 Prediction and Validation of Rotor Loads Using ONERA Unsteady Aerodynamics (M.S. Dissertation of Pierre-Yves Ouillet, 1992)

In this thesis, two semi-empirical dynamic stall models are compared: Leishman-Beddoes model and ONERA model. The theoretical background of both models is first presented. Then, a comparison of two dimensional wing loads for a prescribed oscillatory motion is made. The airfoil used is ONERA OA209 airfoil, with an oscillatory pitch input.

In the two-dimensional parametric study, a reasonable agreement is obtained between both models at low reduced frequencies. Some differences are exhibited at reduced frequencies above 0.05, especially during the reattachment process. Computed normal force and pitching moment coefficients are compared with wind tunnel test data. Again, correlation is good, except for the normal force at higher reduced frequencies where ONERA model predicts slow flow reattachment. The ONERA model, though it does not emphasize the physics of the processes as much as Leishman-Beddoes model, predicts accurately the loads generated on the airfoil in various flight conditions using only a very small number of differential equations. To improve results, it is suggested that the formulation of the empirical time delay used in the stall onset and the modeling of the reattachment process should be refined.

Both models are then included in a comprehensive helicopter code, UMARC (University of Maryland Advanced Rotor Code). The coupled trim results using both aerodynamic models are compared for different advance ratios. Correlation is also made with the flight test data on a Aerospatiale SA 349/2 Gazelle helicopter. The value of the pitch controls as well as the blade response are compared with flight test data. Both models yield comparable results and trends.

3.5 AEROMECHANICAL STABILITY

Aeromechanical stability of a helicopter is a nonlinear phenomenon involving complex interactions of aerodynamic, inertial and elastic forces. The state-of-the-art of aeromechanical stability, including pitch-flap, flap-lag, and ground and air resonance stability, is assessed for articulated, hingeless, bearingless and other advanced rotor systems. Recent designs in rotary-wing technology are tending towards hingeless and bearingless rotors because of reduced costs and maintenance (fewer parts), improved hub designs (simple and clean aerodynamically), and superior handling qualities. Because of stress and weight considerations, hingeless and bearingless rotors are designed as soft-inplane rotors which make them susceptible to aeromechanical stability. Also, the effectiveness of mechanical lag dampers is reduced for hingeless and bearingless rotors because of small displacements near the root. It is therefore a challenging task to stabilize the aeromechanical stability of hingeless and bearingless rotors. Also, the increased forward speed and higher maneuverability expected in future vehicles will further aggravate aeromechanical stability. Furthermore, analyses of hingeless and bearingless rotors become more involved than articulated rotors because of nonlinear couplings caused by elastic defections and the complexity of load paths near the hub. The challenge therefore is to develop and apply reliable prediction techniques to design rotors with favorable structural and aerodynamic couplings so that they are free from any aeromechanical stability.

3.5.1 Air Resonance of Hingeless Rotor Helicopters in Trimmed Forward Flight

Air resonance of a soft inplane hingeless rotor helicopter is examined in hover and forward flight using a simple rigid blade model incorporating blade flap and lag motions, and body pitch and roll motions. Stability is calculated about a propulsive coupled trim condition obtained using a finite element in time approach for blade response and a force summation method for hub loads. The linearized stability equations are transformed into fixed system (multi-blade) coordinates and solved via Floquet analysis. Predicted stability correlates well with experimental results. Both shaft fixed flap-lag stability and air resonance damping improve in forward flight (above an advance ratio of .2) largely as a result of changes in the vehicle trim solution. The effects of variations of several design parameters are investigated systematically.

The significant physical phenomenon in air resonance is a coupling of the blade regressing lag mode with the regressing flap/body roll mode, and, to a lesser extent, the gyroscopic body pitch/roll mode. No significant variation in the frequency relationships among these modes was found in forward flight. In hover, the full vehicle model (flap-lag-pitch-roll) is weakly unstable despite positive flap-lag model stability. The motions of the two systems are also quite different, in particular with regard to the motion of the rotor disk with respect to the air mass. Conversely, flap-lag instabilities of the shaft-fixed type may occur for rotors with reactionless flap and lag modes even when the aircraft is free from air resonance. Compared with the uniform inflow model, the Drees inflow model has little effect on the stability results. The dynamic inflow model, however, resulted in increased stability over the entire airspeed range. For the aircraft examined, stability in hover is sensitive to variations in roll inertia, but nearly insensitive to variations in pitch inertia. In forward flight at advance ratio of .4, the roll inertia seems to play a more significant role. Stable combinations of flap and lag frequencies in hover were also stable at an advance ratio of .4. At the higher advance ratios, the variations in flap frequency influence the stability indirectly through changes in the trim solution. Negative pitch-lag coupling can be effective in improving stability in both hover and forward flight. Pitch-flap coupling has a less significant effect. For the configuration examined, inclusion of structural coupling had less significant effect.

3.5.2 Air Resonance Stability of Hingeless Rotors in Forward Flight

Air resonance in forward flight is examined for hingeless rotors using a finite element formulation. The fuselage is modeled as a rigid body undergoing five degrees of motion and the blade is modeled as an elastic beam undergoing flap bending, lag bending, elastic twist and axial deformation. The vehicle trim and blade steady response solutions are calculated as one coupled solution using a modified Newton method. The blade response is calculated using a finite element method in time after the nonlinear finite element equations in space are transformed to normal mode equations. Unsteady aerodynamic effects are included using dynamic inflow modeling. The linearized periodic coupled rotor-body perturbation equations in the fixed frame are solved for stability using Floquet transition matrix theory as well as constant coefficient approximation. Good correlation of predicted results with experimental data were shown for ground resonance and air resonance. The inclusion of dynamic inflow improved the prediction of stability. Systematic parametric studies were then carried out to examine the effects of several design variables on air resonance stability in forward flight. For modeling of air resonance stability of a hingeless rotor, the inclusion of pitch and roll rigid body airframe modes is suffice. Blade lag stiffness and fuselage roll inertia were found to have powerful influence on air resonance stability.

3.5.3 Aeromechanical Stability of Helicopters with Dissimilar Blades

(Ph. D. Dissertation of James M. Wang, 1992)

The effects of blade-to-blade dissimilarities on helicopter aeromechanical stability and hub loads are examined for articulated, hingeless, and bearingless rotors. The study includes one or more lag dampers inoperative, unbalance in blade mass, dissimilarities in blade stiffnesses and aerodynamics. The physical mechanisms of helicopter air and ground resonance is examined in depth for helicopters with and without blade-to-blade dissimilarities. The study is conducted using a rigid blade model, and a finite element analysis that includes rotor aerodynamics, elastic blade deformations, and five rigid fuselage motions. The analytical results are validated against wind tunnel data for a hingeless rotor without dissimilarity, and a bearingless rotor with dissimilarities. It is shown that certain types of blade dissimilarities can improve the regressing lag stability without significant hub load penalties. A sensitivity study shows only small amount of dissimilarity is necessary to improve aeromechanical stability. When the stability of the least stable mode is improved, the stability of the other modes is decreased because the total damping in the system is conserved. When some of the lead-lag dampers have failed, the rotor can still be stable. It is the energy dissipation capability of the entire rotor/body system that determines the overall stability.

3.5.4 Aeromechanical Stability of an Advanced Geometry Rotor

Advanced geometry blades are characterized by variable sweep, droop, twist and planform taper. Such blades are receiving increasing attention by the designers as a viable means to alleviate compressibility drag, stall effects and acoustic noise. Swept tip, for example, reduces the incident Mach number on the advancing blade, thereby reducing the drag associated with transonic flow conditions. Advanced tips also appear attractive for reducing vibratory hub loads and for enhancement of aeromechanical stability. With the potential application of composite materials, feasibility of using advanced geometry rotors has increased substantially.

Early research on swept-tip blades was primarily focused on aerodynamic performance characterization of blades. These studies, while clearly showing reductions in power requirement, also pointed out the need for realistic aeroelastic modeling of the swept-tip blades for accurate calculation of aerodynamic loads. Full benefits of an advanced geometry blade cannot be realized without a thorough understanding of its dynamic and aeromechanical stability characteristics. The model must capture important bending-torsion and lag-axial couplings introduced by variable geometry. It must also capture the dynamic interaction between fuselage and rotor, which becomes quite involved because of sweep. Because of the complexity of the problem, only limited attempts have been made to study the dynamic behavior of a swept-tip rotor, much less the aeromechanical stability.

Benquet and Chopra developed an aeroelastic formulation for the advanced tip using a finite element method based on Hamilton's principle. It covered tip sweep, anhedral, planform taper and twist for the blade only. Blade response and loads in forward flight were calculated for blades with varying tip sweep and anhedral. Linear transformation relations between the swept tip and main blade were used. Kim extended the formulation to include nonlinear transformation relations between the tip and the main inboard blade for moderate rotations. Three-dimensional aerodynamics was also included. Results indicated that swept tip was very effective in reducing shock strength on the advancing side and the flap and torsional oscillatory responses. Tip anhedral increased the shock intensity in the first quadrant ($0^{o} < \psi < 90^{o}$), and decreased it in the second quadrant ($90^{o} < \psi < 180^{o}$). Tip anhedral also showed considerable influence on flap dynamics.

Variable geometry introduces certain dynamic couplings which are absent for a straight blade. An important feature is the presence of strong centrifugal force components normal to axes of blade segments. Another key feature of advanced geometry blade is the continuous reorientation of a swept-segment elastic axis as blade pitch setting varies over azimuth. This reorientation causes continuous variation in the torsion-bending couplings which have an important effect on blade dynamics, in particular the torsional dynamics. Also, the geometric nonlinearities, which are important for a straight blade, take on a much stronger role for the advanced geometry blade. Sweep and droop in fact generate additional nonlinear terms which are absent for a straight blade.

The dynamic analysis becomes much more involved when fuselage motion is coupled with the advanced geometry rotor motion. A mathematical model of the advanced geometry blade must capture all the aforementioned nonlinearities and couplings properly to accurately predict the rotorcraft dynamics.

A new formulation is developed which models varying sweep, droop, twist and planform along the length of the blade. This formulation represents considerable refinements over previous works, in particular the way time-varying blade pitch control is translated into the flap, lag and pitch motions of the inclined segments. Various kinematic transformations, centrifugal stiffening terms, and Coriolis forces are rederived more rigorously. Equations of motion are discretized, as was done by previous researchers, using finite element approach based on Hamilton's principle. The formulation is developed for a general tip planform, arbitrary sweep and anhedral angles, and accounts for general variations of mass, stiffness and geometric properties along the blade. New inter-segment compatibility relations are derived which include important nonlinear terms and are consistent with the sequence-independent (non-Eulerian) rotational degrees of freedom. The formulation is extended to include fuselage dynamic interaction with the advanced geometry blade.

Extensive studies have been conducted to investigate the effect of blade sweep and droop on the blade aeroelastic response, rotor stability, and aeromechanical stability. Sample results are presented to show the effect of tip sweep on the blade load and stability of a soft-inplane hingeless rotor for hub-fixed condition. Figure 1 shows the effect of sweep on the blade torsional moment,. Note that the mean value of the nose-down pitching moment as well as higher harmonic components of the torsion load increase with sweep.

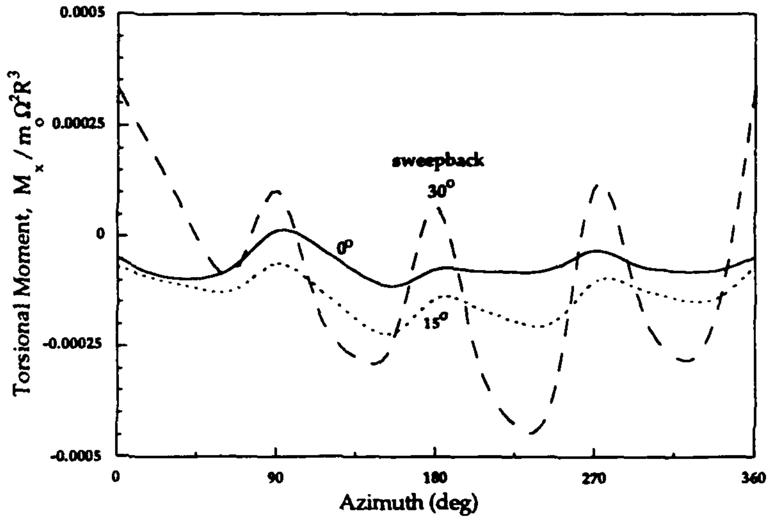


Figure 1: Effect of sweep on torsional moment at the blade root
(m = 0.3, G_T = 0.10)

Figure 2 presents aeroelastic stability results for a simple hover case at three thrust levels. Results are presented in terms of the damping of the second lag mode which is the least damped amongst all the modes (even compared to the first lag mode which usually is the least damped mode). Note first that the second lag mode is only marginally stable when the blade is straight (zero degree sweep). A little change in sweepback appreciably increases the second lag mode damping till a sweepback angle of about 30 degrees is reached. Further sweepback causes drop of the modal damping. The effect of forward sweep is negligible till 10 degrees; beyond this angle, forward sweep has a beneficial effect on the second lag mode stability. Also note that for an unswept blade, the second lag mode damping is insensitive to variations in the thrust level. The lag damping increases substantially with thrust level.

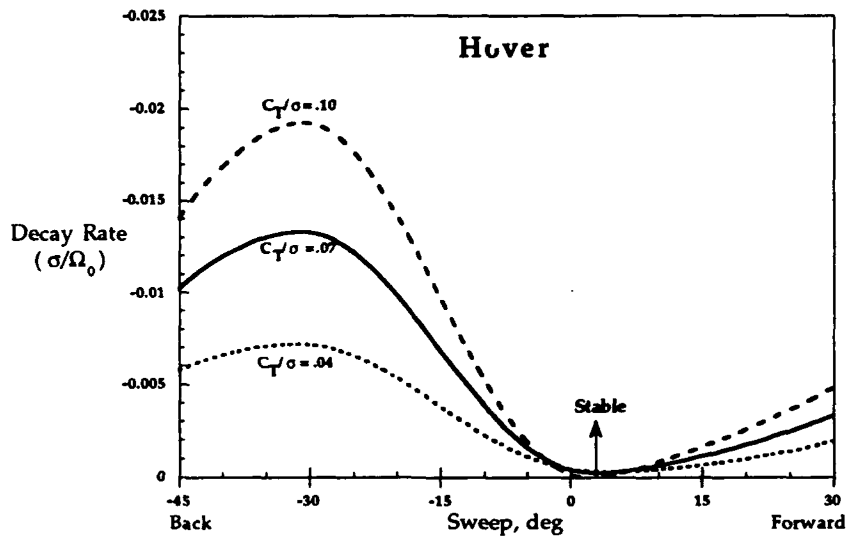


Figure 2: Effect of sweep on second lag mode damping (tip = 20%R)

The formulation, involving computation of advanced geometry blade structural and aerodynamic matrices, coupled blade-fuselage matrices and inter-segment compatibility relations, has been successfully integrated with the University of Maryland Advanced Rotorcraft Code (UMARC).

3.6 HIGHER HARMONIC CONTROL (HHC)

Higher harmonic control (HHC) is an active vibration control approach which has been shown to be quite effective in suppressing helicopter vibration. The primary source of helicopter vibration is the higher harmonic blade loads generated by the aerodynamic environment at the rotor disk. For N-bladed rotor, the oscillatory (N-1)P, NP and (N+1)P blade loads are transmitted as exciting hub forces and moments to the airframe at a dominant frequency of N per rev. An HHC system excites the blade pitch at higher harmonic of rotor rotational speed, generating new unsteady airloads, which in combination with the new inertial loads, cancel the harmonics of blade loads that cause vibration. Therefore, the vibrations are suppressed at the source. Although there are many ways to implement HHC on a rotor system, the most popular approach is blade root feathering using swashplate oscillations. By means of servo-actuators, the swashplate is excited in the collective, longitudinal cyclic, and lateral cyclic at NP resulting in blade pitch oscillations at three distinct frequencies of (N-1)P, NP, and (N+1)P in the rotating frame. With the availability of high speed micro-processors and with advances in servo-actuator technology, there appears to be great potential for HHC as an effective approach to control helicopter vibration under varying flight conditions.

From existing analytical and experimental investigations on I HC systems, it has been found that the higher harmonic blade pitch needed to suppress vibrations is reasonable (typically less than 2 deg.), and therefore the power requirements for the actuators are manageable. However, most of the existing studies have been confined to be well within the normal flight boundary, where the effects of retreating blade stall and advancing blade compressibility are small. For helicopters operating near the flight boundary, however, the higher harmonic blade pitch used for vibration suppression may introduce an more significant level of blade stall. Since a successful HHC system must operate effectively in such a severe aerodynamic environment, it is of great interest to investigate the performance of such a system at these flight conditions. The objective of this research is to make systematic investigation to calculate HHC inputs and associated actuator power required to suppress the vibratory hub loads at high forward speeds and thrust levels, and for different articulated and hingeless rotor systems.

3.6.1 Higher Harmonic Control Analysis for Vibration Reduction of Helicopter Rotor Systems at High Speed and Thrust (Ph. D. Dissertation of Khanh Q. Nguyen, 1989)

An advanced higher harmonic control (HHC) analysis has been developed and applied to investigate its effect on vibration reduction levels, blade and control system fatigue loads, rotor performance, and power requirements of servo-actuators. The analysis is based on a finite element method in space and time. A nonlinear time domain unsteady aerodynamic model, based on the indicial response formulation, is used to calculate the airloads. The rotor induced inflow is computed using a free wake model. The vehicle trim controls and blade steady responses are solved as one coupled solution using a modified Newton method. A linear frequency-domain quasi-steady transfer matrix is used to relate the harmonics of the vibratory hub loads to the harmonics of the HHC inputs. Optimal HHC is calculated from the minimization of the vibratory hub loads expressed in term of a quadratic performance index. Predicted vibratory hub shears are correlated with wind tunnel data. The fixed-gain HHC controller suppresses completely the vibratory hub shears for most of steady or quasi-steady flight conditions. HHC actuator amplitudes and power increase significantly at high forward speeds (above 100 knots). Due to the applied HHC, the blade torsional stresses and control loads are increased substantially. For flight conditions where the blades are stalled considerably, the HHC input-output model is quite non-linear. For such cases, the adaptive-gain controller is effective in suppressing vibratory hub loads, even though HHC may actually increase stall areas on the rotor disk. The fixed-gain controller performs poorly for such flight conditions. Comparison study of different rotor systems indicates that a soft-inplane hingeless rotor requires less actuator power at high speeds (above 130 knots) than an articulated rotor, and a stiff-inplane hingeless rotor generally requires more actuator power than an articulated or a soft-inplane hingeless rotors. Parametric studies for a hingeless rotor operating in a transition flight regime and for an articulated rotor operating at the level-flight boundary (high speed and high thrust conditions) indicate that blade parameters including flap, lag- torsion stiffness distributions, linear pretwist, chordwise offset of center-of-mass from elastic axis and chordwise offset of elastic axis from aerodynamic center all have some influences on the actuator power requirements. For details, see Refs. [Nguy88, Nguy90a, Nguy90b, Nguy91]

3.7 TAIL ROTOR DYNAMICS

The tail rotor operates in a very complex aerodynamic environment as a result of the forward flight of the helicopter, sidewind, main rotor wake interactions and its own induced wake. The severity of the wake interactions depends on the location of the tail rotor with respect to the main rotor, characteristics of the main rotor and flight condition.

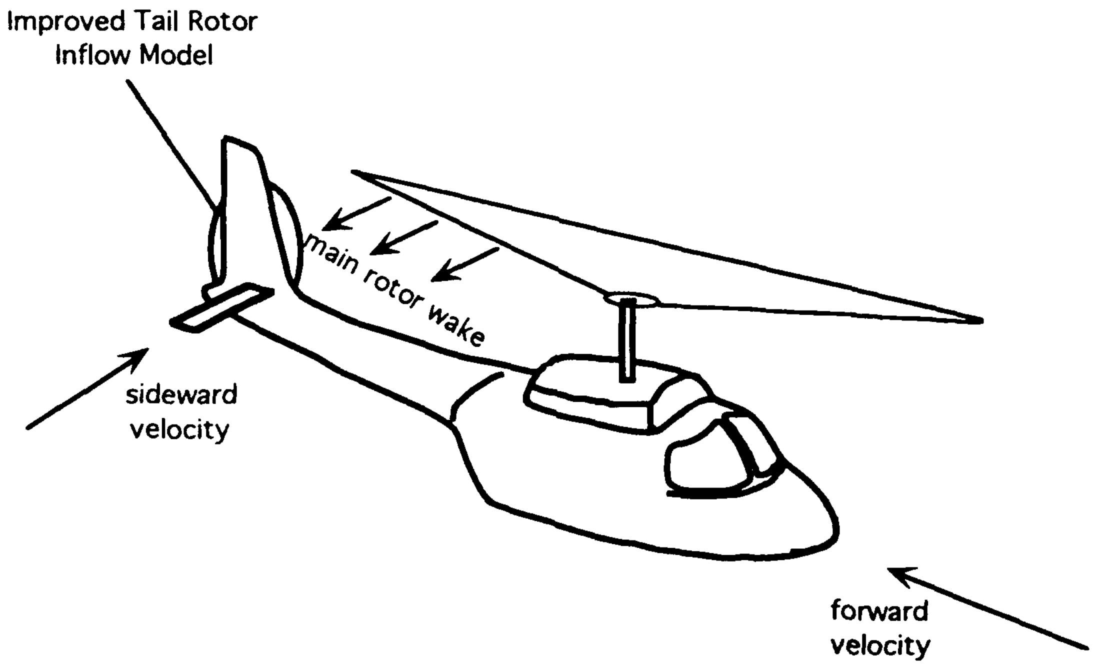


Figure 1: Helicopter exposed to side wind

3.7.1 Prediction of Yaw Control Effectiveness and Tail Rotor Loads

The first objective of this research is to develop an efficient and accurate isolated tail rotor inflow model that works in the normal working state, windmill brake state and vortex ring state of operation as well as in forward flight condition. As far as possible, a minimum amount of empiricism should be incorporated. The variation of induced velocity with climb velocity in a pure axial flight condition is extended to forward flight assuming the presence of a slipstream. Since the tail rotor often operates at high collective pitch settings exceeding 12 degrees, linear airfoil characteristics would not be sufficient for predicting the thrust capabilities of the tail rotor. In this analysis, airfoil data with stall and compressibility effects have been used. Validation of the tail rotor model is carried out using wind tunnel test data.

The second objective is to study the wake behind the main rotor and understand its influence on the tail rotor. Simple wake models of the main rotor based on momentum theory, such as the uniform inflow and linear inflow models, do not capture the essence of the flow environment behind the rotor. Hence more sophisticated wake models such as the prescribed wake and free wake models are necessary for this type of analysis. The wake behind the main rotor is studied for an SH-2 Kaman Seasprite helicopter for a forward flight velocity of 45 knots (advance ratio of 0.11). using the prescribed and free wake models of UMARC (University of Maryland Advanced Rotor Code). The wake shows a considerable interaction with the tail rotor. Validation studies using experimental data have also been conducted to check whether the converged wake obtained using a free wake analysis is realistic for the prediction of flow field velocity components at the tail rotor. The results show that the free wake analysis predicts the induced velocity in the lateral direction fairly well.

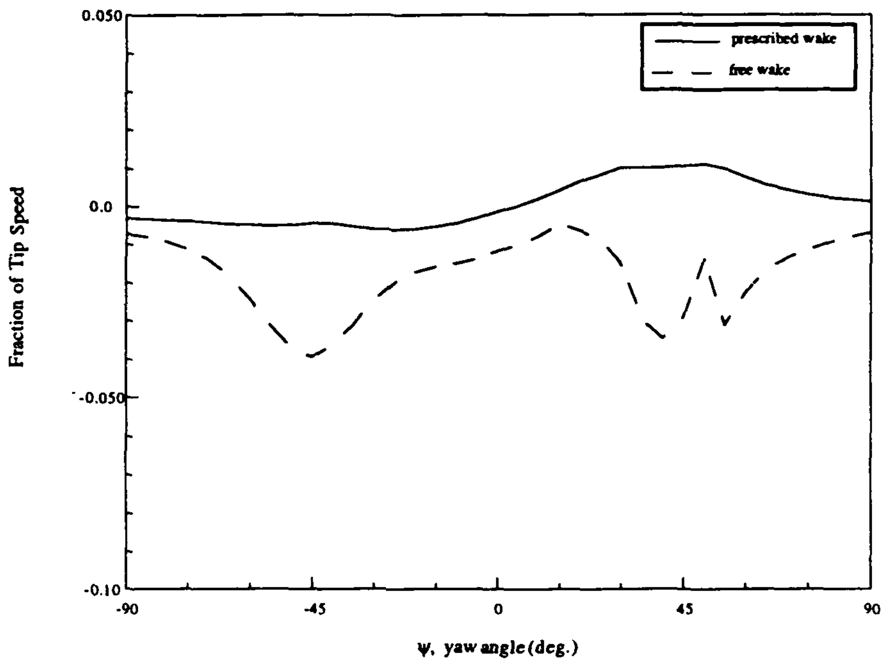


Figure 2: SH-2 Wake-induced Tail Rotor Inflow (V=45 knots, m=0.11)

The third objective is to examine the induced velocity distribution and oscillatory hub loads at the tail rotor for different flight conditions. Figure 2 shows the prediction of additional tail rotor inflow due to the main rotor wake at an advance ratio of 0.11 for the SH-2 rotor using prescribed and free wake analyses for different yaw angles. The undistorted geometry of the prescribed wake induces a much smaller inflow as compared to the distorted free wake. The velocities induced by the free wake geometry are comparable in magnitude to the tail rotor induced inflow of 0.047 obtained neglecting wake interactions.

The next objective is to predict the loss of yaw control due to insufficient tail rotor thrust resulting from sidewinds and from interactional effects of the main rotor wake at the tail rotor hub and to predict the change in trim controls and vibratory loads of an elastic tail rotor using a coupled trim procedure.

3.8 AEROELASTIC OPTIMIZATION

Helicopters are susceptible to high vibrations, initiated primarily at the rotor blades. The oscillatory forces and moments from the blades are transmitted to the hub as principal sources of helicopter vibration. One direct approach to reduce vibration is to design a rotor which inherently produces low oscillatory hub loads. By making an optimum selection of structural, inertial, and aerodynamic characteristics of the blades, it becomes possible to minimize the source of vibration and keep the blades aeroelatically stable. An automated methodology to accomplish this objective is referred to as aeroelastic optimization. With an enhanced understanding of the dynamics of rotary-wing systems, it is now becoming feasible to apply aeroelastic optimization to the rotorcraft field. The potential of structural optimization is further expanded with the application of composites in blade construction, which permits great flexibility in tailoring structural characteristics. Also, the techniques of modern structural optimization have become more refined, the data processing capability of modern computers has grown substantially, and it is becoming attractive to implement aeroelastic optimization to complex rotor systems.

The objective of this research is to investigate the structural optimization of a hingeless rotor to reduce oscillatory hub loads while maintaining aeroelastic stability in forward flight.

Most studies on aeroelastic optimization use finite difference methods for calculating the gradients of objective functions and constraints. Because of large computer time requirements, such studies are restrictive in terms of objective function, design variables and constraints. At Maryland, Lim in his dissertation addressed this problem by developing an efficient analytical formulation to calculate sensitivities of blade response, hub loads and blade stability with respect to different design variables. The sensitivity analysis is performed as an integral part of the rotor aeroelastic analysis. A comprehensive study was performed to minimize all the vibratory shears and moments for helicopter rotor blades with constraints on blade stability in forward flight. Although the benefits of using analytical sensitivity derivatives in structural optimization is well known, this is the first time that such an analysis was developed for a complex aeroelastic problem, with considerable savings in computer time to achieve the optimum solution compared to a finite difference approach. Two types of blade structural representations were used. One was a generic rotor blade whose structural properties were described in terms of blade stiffnesses, regardless of the cross-sectional details. In the second type, the blade structural characteristics were defined in terms of spar geometry of a closed-cell box beam.

3.8.1 Aeroelastic Optimization of a Helicopter Rotor

(Ph. D. Dissertation of Joon W. Lim, 1988)

Structural optimization of a hingeless rotor is investigated to reduce oscillatory hub loads while maintaining aeroelastic stability in forward flight. Design variables include spanwise distribution of nonstructural mass, chordwise location of blade center of gravity and blade bending stiffnesses (flap, lag and torsion). The objective function is expressed as a function of one or more components of oscillatory hub loads with suitable weighting functions. For inequality constraints, the aeroelastic stability of the blade in forward flight is selected to keep the blade aeroelastically stable. A comprehensive aeroelastic analysis of rotors, based on a finite element method in space and time, is linked with optimization algorithms to perform optimization of rotor blades. The vehicle trim and blade steady response are calculated iteratively as one coupled solution using a modified Newton method. Eigenvalues corresponding to different blade modes are calculated using Floquet transition matrix theory. For the optimization process, a new methodology, direct analytical approach for calculation of sensitivity derivatives of blade response, hub loads and eigenvalues with respect to design variables, is developed. This approach constitutes an integral part of the basic blade response and stability analyses, and reduces the computation time substantially; a 80% reduction of CPU time to achieve an optimum solution as compared to the widely adopted finite difference approach. Systematic sensitivity studies are carried out to assess the importance of several design parameters on vibration reduction of a helicopter. To investigate the influence of design variables on the optimization process, six different combinations of design variables are chosen. The "best optimum" solution is achieved by distribution of nonstructural masses and blade bending stiffnesses (flap, lag and torsion), and removing the blade c.g. offset as a design variable. For this case, a 60-90% reduction in all six 4/rev hub loads is achieved for a four-bladed soft-inplane rotor.

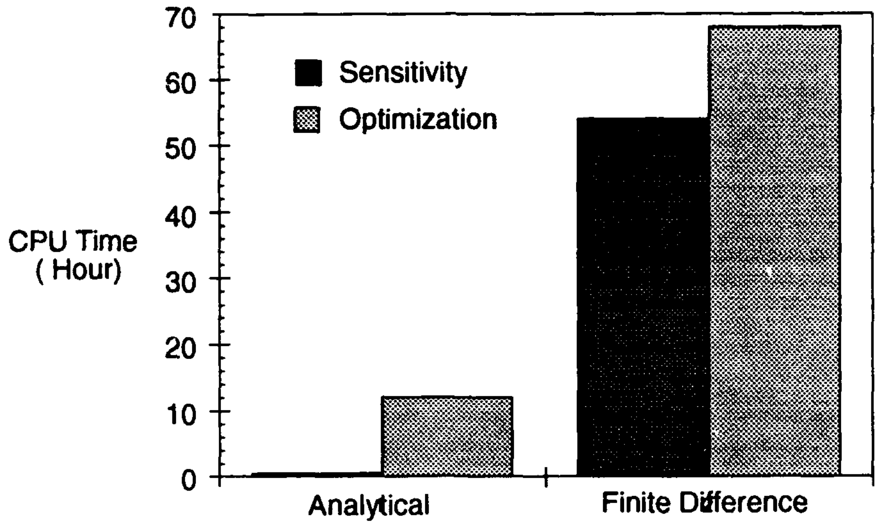


Figure 1: Comparison of CPU time for optimization process

3.8.2 Aeroelastic Optimization of a Helicopter Rotor Using Detailed Section Representation

A structural optimization analysis of a hingeless helicopter rotor is developed and applied with the objective of reducing oscillatory hub loads in forward flight. The aeroelastic analysis of the rotor is based on a finite element method in space and time and is linked with automated optimization algorithms. Two types of structural blade representations are used: a generic stiffness-distribution beam and a single-cell, thin-walled beam. For the generic beam representation, the design variables are nonstructural mass and its placement, chordwise center of gravity offset from the elastic axis, and structural stiffness (flap, lag, and torsion). For the second type of structural representation, spar width, height, and thickness are used as design variables instead of blade stiffness. Constraints on frequency placement, autorotational inertia, and aeroelastic stability of the blade are included. Sensitivity derivatives are efficiently calculated using a direct analytical approach, with a resulting 80% reduction in total CPU time required to obtain an optimum solution compared with a commonly used finite-difference approach. Optimum solutions for a four-bladed soft-inplane hingeless rotor resulted in reductions of 25 - 77% for the generic blade, and 30 - 50% for the box-beam blade relative to baseline values of the objective function that was comprised of all six components of hub load. Gains become smaller if initially infeasible design is pursued. For example, if a behavior constrain of 1% lag damping is enforced, the objective function is reduced by 25% for the optimized solution instead of the 77% achieved with no active constraint. For a box beam blade, a 33% reduction of the objective function was achieved when the flap frequency constraint became active, a 32% reduction was obtained when the lag mode stability and flap frequency constraints became active, and the objective function was reduced by 51% from the baseline value when no behavior constraint was imposed.

3.8.3 Aeroelastic Optimization of an Advanced Geometry Helicopter Rotor

Sensitivity derivatives of blade loads and aeroelastic stability of a helicopter rotor in forward flight are calculated as an integral part of a basic aeroelastic analysis using a direct analytical approach. Design variables include nonstructural mass and its placement, chordwise offset of blade center of gravity and aerodynamic center from the elastic axis, blade bending stiffnesses (flap, lag, torsion) and tip geometry (sweep, anhedral, pretwist, and planform taper). By means of a sensitivity study, the importance of different design variables on oscillatory hub loads and damping of blade modes is examined. Aeroelastic and sensitivity analyses of the rotor based on a finite element method in space and time are linked with automated optimization algorithms to perform optimization studies of rotor blades. The objective function minimizes oscillatory hub loads with constraints on frequency placement, autorotational inertia and aeroelastic stability of the blade in forward flight. Optimum design solutions, calculated for a four-bladed, soft-inplane hingeless rotor achieved a reduction of 25 - 60 percent of all 4/rev loads. Using tip sweep as a design variable alone can give vibration reduction of about 10% Blade sweep anhedral, twist and planform taper reduce the objective function by about 20% when compared to an unswept and untapered blade. Tip anhedral results in reduction of the objective function if the tip sweep is present. The optimized advanced geometry configuration consists of tip sweep, anhedral, nose down twist and taper.

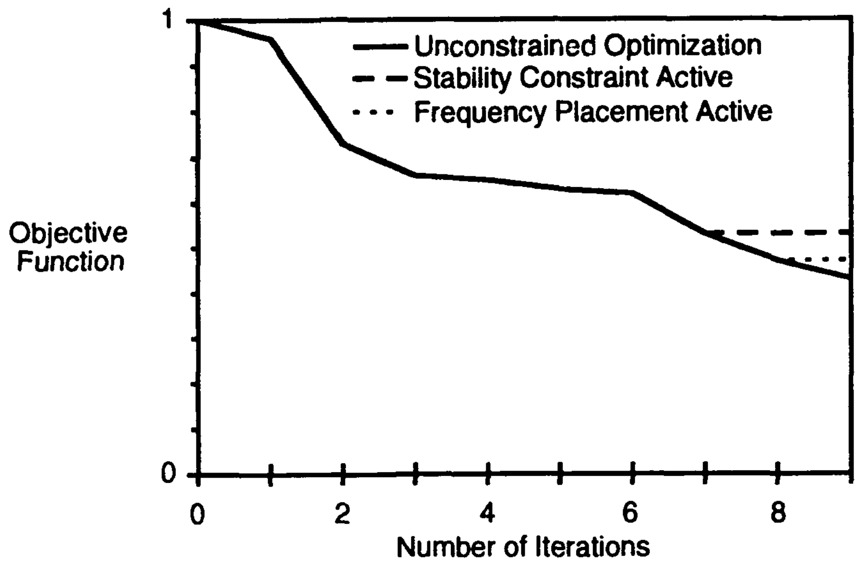


Figure 2: Constrained Optimization History for Advanced Geometry Helicopter Rotor ($C_T/\sigma = 0.07, \mu = 0.3$)

3.8.4 Aeroelastic Optimization of Composite Helicopter Rotor

Sensitivity derivatives of blade loads and aeroelastic stability of a composite helicopter rotor in forward flight are calculated as an integral part of a basic aeroelastic analysis using a directly analytical approach. Design variables are the ply angles of the laminated walls of the box-beam spar used to model the composite blade. By means of a parametric study, the influence of the ply angles on the blade elastic stiffnesses, 4/rev rotor loads and aeroelastic stability are examined for a four-bladed, soft-inplane, hingeless rotor. Aeroelastic and sensitivity analyses of the rotor based on a finite element in space and time are linked with an automated optimization algorithm to perform optimization studies of composite rotor blades. The objective function minimizes the vibratory hub loads with constraints on frequency placement and aeroelastic stability of the blade in forward flight. Optimum design solution for a box-beam configuration with no elastic couplings shows a reduction of about 40 percent in the objective function. The influence of elastic couplings on the 4/rev loads corresponding to the optimum solutions is relatively small with reductions in the objective function of less than 10 percent. The effect of pitch-lag coupling in stabilizing the lag mode is significant. Starting from an initially infeasible design, the optimum design solution for a box-beam configuration with pitch-lag coupling shows an increase in lag damping of over 100 percent. Starting with an initially infeasible design for a requirement of 3% damping on the lag mode for aeroelastic stability, the symmetric layup incorporating negative pitch-lag coupling shows an increase of objective function by 5% compared to the baseline value and an increase in lag damping of about 130%

3.8.5 Aeroelastic Optimization of a Helicopter Rotor with Multi-Cell Section and Composite Tailoring

A sensitivity analysis and aeroelastic optimization for a four-bladed, soft-inplane, uniform, composite hingeless rotor with a generic cross-section is developed using an analytical approach. Shear degrees of freedom are eliminated by using static condensation. The composite blade spar is modeled as a single-cell box-beam as well as a two-cell box-beam. The design variables used in this study are the ply angles of the laminated walls of the composite box-beam. Aeroelastic and sensitivity analyses of the rotor based on a finite element in space and time are linked to an automated algorithm to perform optimization studies. The objective function minimizes the 4/rev hub loads, with constraints on blade frequency and aeroelastic stability in forward flight. A sensitivity study of the 4/rev loads, blade stability and frequency show that torsion stiffness is a dominant section property for the optimization problem. Optimum design solutions for a two-cell box-beam configuration with no elastic coupling show a reduction of more than 10 percent in the objective function from the starting design. The influence of elastic coupling shows an additional reduction in the objective function of over 10 percent. Starting from an initially infeasible design with a stability margin of 1% in lag mode damping, the optimum design solution for a two-cell box-beam configuration with negative pitch-lag and positive extension-torsion coupling results in an increase in lag mode damping of over 50 percent compared to the baseline layup. This increase in stability comes at the expense of an increase in the objective function of about 10%.

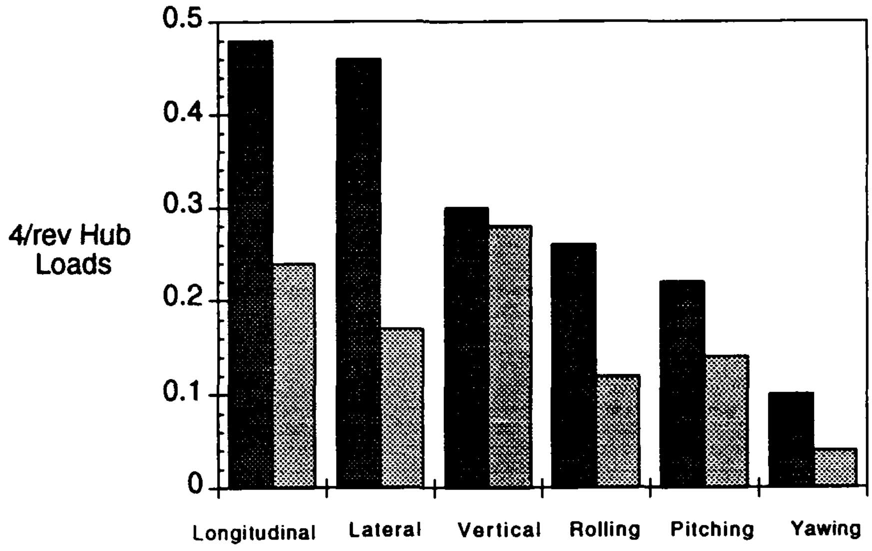


Figure 3 Optimum 4/rev Oscillatory Loads

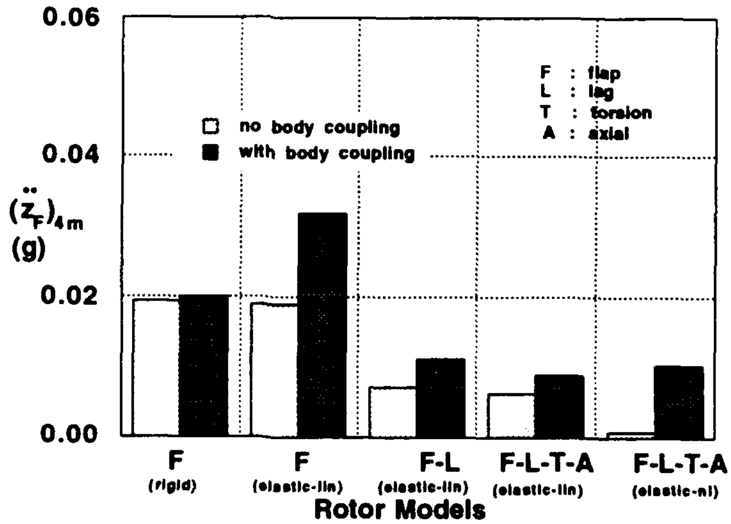
3.9 COUPLED ROTOR-BODY VIBRATION

Estimation of fuselage vibration is one of the most challenging tasks in the rotorcraft field. For accurate estimation of vibration, it requires a sophisticated mathematical modeling of airframe as well as rotor. To make the analysis manageable, rotor and fuselage are usually considered separately and coupling is achieved through an iterative procedure. The rotor being the main source of oscillatory forces caused by complex and nonlinear interactions between elastic, aerodynamic, and inertial forces is a key ingredient to vibration analysis. The rotor blades are normally modeled as elastic beams undergoing moderately large deflections. For an N-bladed tracked rotor, the oscillatory blade forces are transmitted as vibratory hub forces and moments to the fuselage at a dominant frequency of N/rev. Magnitudes of hub forces involving higher frequencies such as 2N/rev and 3N/rev are generally small. Even to cover N/rev forced response, many airframe modes participate. Therefore, it becomes necessary to formulate a detailed structural modeling of the fuselage.

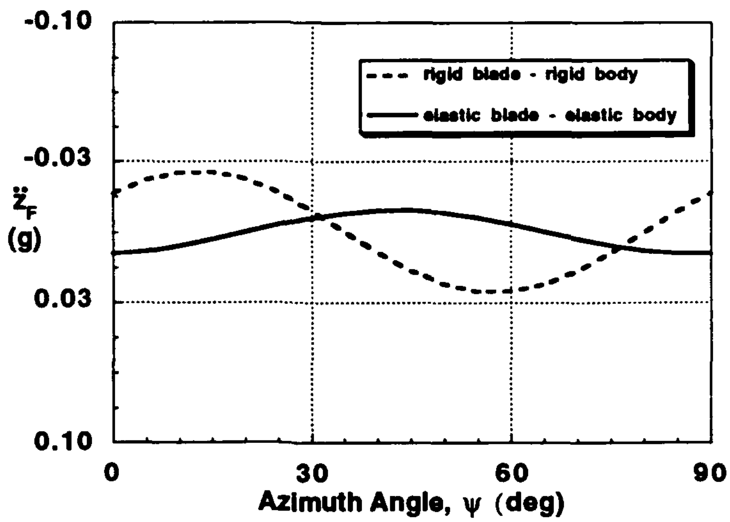
Coupled rotor-body vibration analysis has been attempted by many researchers with varying levels of modeling sophistication, solution procedure and approximations. Most available analyses use either simple rotor modeling or simple fuselage modeling. These can utmost be used to predict qualitative trends of rotor-body couplings. For an accurate estimation of vibration, it is essential to simulate a realistic representation of the body coupled to a sophisticated mathematical of the rotor. This requires the derivation of a consistent set of rotor-body dynamic equations and then solve these using an efficient procedure.

3.9.1 Effect of Modeling Techniques in the Coupled Rotor-Body Vibration Analysis

Currently, most studies incorporate either simple rotor modeling or simple body modeling to predict vibration. Though these models can provide qualitative trends, it is essential to examine their relative significance. The present study is directed towards assessing various mathematical models of rotors and airframe to develop rotor-body coupled vibration analysis. For this purpose, five rotor models ranging from simple rigid flap model to nonlinear coupled flap-lag-torsion-axial elastic model, and three airframe models ranging from six degree of freedom rigid model to distributed elastic line model are formulated. The rotor-body coupling is achieved through an implicit procedure. For numerical study, an elastic line model of the Bell Huey AH-1G helicopter airframe is coupled to a four bladed soft-inplane hingeless rotor. Fuselage accelerations were calculated at the pilot seat using different rotor-body idealizations. The study shows simpler blade models *over-predict vibration* along vertical, pitch, and roll directions and under-predict vibration along longitudinal, lateral, and yaw directions. For proper accounting of rotor-body coupling effects, it is necessary to include a detailed elastic model of airframe.

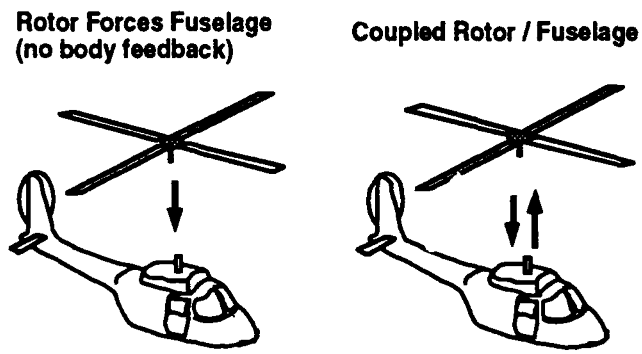


(a)



(b)

Fig.1 Vertical Acceleration at Pilot Location



3.10 DEVELOPMENT OF UMARC

The University of Maryland Advanced Rotorcraft Code (UMARC) has been developed in response to needs of the researchers and the rotorcraft industry for a single comprehensive code which can readily model existing as well as evolving advanced rotor designs, and provide for a multitude of analysis options. Prior to the development of the code, graduate students at the University of Maryland had developed several refined codes but with specific objectives, e.g., nonlinear aeroelastic trim, blade flap-lag-torsion stability in forward flight, blade and hub loads, air/ground resonance, three dimensional gust and vortex field response, circulation control aerodynamics, composite rotors, higher harmonic control, air/ground resonance, and aeroelastic optimization. These codes, developed by individual researchers with limited objectives, lacked user-friendliness, modularity, numerical robustness and flexibility for further expansion.

Specialized features of these codes were first extensively upgraded and integrated into a single code. This constituted the first phase of the UMARC development. During the second phase, software features were introduced, e.g., modularity, parameterized dimensioning, clear programming logic and user-friendly interface. Also, numerical schemes were made more robust and time-efficient. Theory bases were either revised or replaced by more rigorous ones. Next, a Theory Manual was written describing UMARC theory bases and implementation schemes. The code, supplemented by the Theory Manual, was delivered to various rotorcraft research organizations for test studies.

The UMARC development is currently in its third phase. Based on in-house validation studies, and suggestions from the rotorcraft industry, numerous upgrades have been introduced in UMARC. The resulting code, designated Version 1, is being extensively and successfully used at both the academia and rotorcraft industry.

Major modeling and analysis capabilities of UMARC are summarized in the figure below. The key features of UMARC are its underlying finite element methodology, sophisticated aerodynamic models, rotor configuration adaptability (ranging from the conventional articulated rotor with kinematic couplings to the evolving bearingless rotor designs with composite blades), and multitudinous analysis capability including nonlinear aeroelastic coupled trim, rotor loads, air/ground resonance, and aeroelastic optimization.

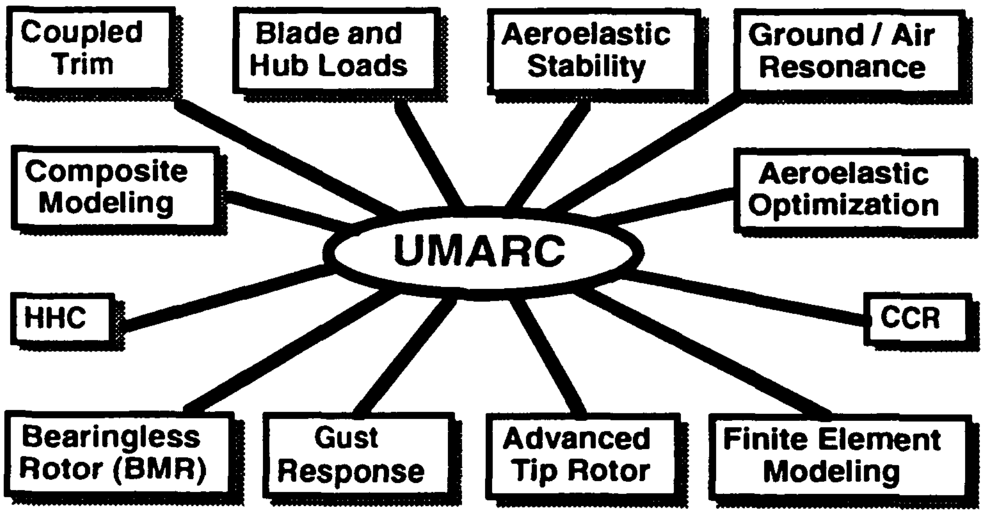


Figure 1: Major Features of UMARC

Figure 2 shows sample results obtained during validation study of the aeromechanical stability analysis. Results are correlated with experimental data obtained by Bousman from a soft-inplane hingeless rotor model. Correlation is satisfactory.

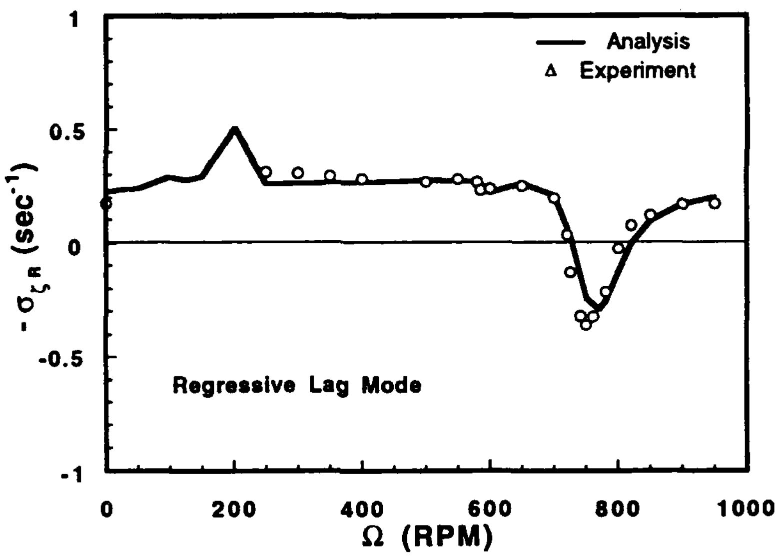


Figure 2: Rotor Lag Mode Damping vs Rotor Speed (hingeless rotor in hover)

It should be emphasized that UMARC has been written to facilitate expandability in future. Continual upgrades will require continual validation studies. Elaborate validation studies and code upgrades are already planned for the near future. Research is in progress to refine composite blade modeling for warping, transverse shear and ply in-plane elasticity. Plans are underway to adapt UMARC to system identification techniques and smart structure applications.

4.0 FLIGHT DYNAMICS

At the beginning of the period covered by this report (1987) the Rotorcraft Center began in earnest a research effort in the area of flight dynamics and control. The general motivation of these activities was the realization that the next generation of military helicopters would be equipped with high bandwidth rotor systems, such as hingeless and bearingless rotor systems. For these helicopter configurations, the traditional conceptual separation between rotor dynamics and fuselage rigid body dynamics would not be as legitimate as for teetering and articulated rotor helicopters, especially in the presence of the high performance flight control systems required to satisfy the new handling qualities specifications ADS-33C. In other words, the traditional flight dynamics problems would have to be considered as integrated flight dynamics/aeroelasticity problems, and formulated and solved as such.

The main activity in the period 1987-1992 was in the formulation and solution of multidisciplinary mathematical models of helicopter flight dynamics, which included both the rigid body dynamics of the helicopter and the dynamics of flexible main rotor blades. This activity proceeded along two converging lines, namely: (i) the extension of traditional aeroelastic stability analyses to account for the large rigid body motions encountered in flight dynamics applications, and to account for the dynamic coupling between the rotor and the fuselage, and (ii) the extension of traditional flight dynamics analyses to more "state-space oriented" formulations, more suitable for the design and validation of advanced flight control systems. At the present time, both avenues have converged into a unified mathematical model suitable for both flight dynamics and aeroelasticity applications. The various steps carried out in achieving this objectives, and the most significant results achieved in the process are summarized below.

As far as the "aeroelasticity" path is concerned, a fixed-shaft aeroelastic stability and response analysis for straight conditions was the starting point in late 1987. The analysis was capable of modeling isotropic hingeless and articulated rotor blades, with straight or swept tips. The aerodynamic portion of the analysis was treated with a so-called "implicit" or "numerical" formulation. This means that the various components of the aerodynamic model (such as the various expressions describing the motion of a point on the blade, the coordinate transformations required to transform the aerodynamic loads into the undeformed blade coordinate system, and the lift, drag and pitching moments acting on the blade element) were not expanded symbolically, but rather were coded independently and then assembled "numerically" during the solution process. This approach reduced dramatically the effort required to implement the mathematical model, and led to very modular computer programs, in which selected portions of the model could be modified or replaced independently from the others. The aeroelastic analysis included a simple trim procedure (fuselage uncoupled from the rotor), and could predict the steady-state periodic response of the blades and the linearized aeroelastic stability according to Floquet theory for systems with periodic coefficients.

The first extension required to deal with flight dynamics type problem was the ability to include in the blade equations large rigid body motions such as those that could be induced by maneuvers. This was accomplished by (i) deriving expressions for the inertia loads acting on the blade in the presence of large rigid body motions, still in the context of a Newtonian approach (i.e. without using multibody dynamics) and (ii) implementing these expressions using a numerical formulation. At this point the potential of the resulting model was not fully realized because the assumption of a fixed shaft had been retained. However it was clear that future coupled rotor-fuselage dynamic models based on the new equations would be superior to the existing ones, because the limitation that the fuselage motions be small had been removed. This limitation was due to the application of ordering schemes in equations derived by other investigators, and in which the traditional algebraic expansions of the models had been retained.

The next step consisted of introducing a description of actual maneuvers in the mathematical models. The specific maneuver chosen was a steady, coordinated turn at a constant flight path angle, because this is the only rigorously steady maneuver other than straight flight. The idea pursued at that time was to calculate the aeroelastic stability and response characteristics under the assumption that the motion of the hub was prescribed. This was the most logical extension of the concept of fixed hub aeroelastic stability, although it precluded the study of the dynamic coupling between rotor and fuselage. In other words, at this stage the model could not predict air resonance stability characteristics. An important ingredient that needed to be developed in this study was a coupled rotor-fuselage trim procedure valid for turning flight. The rotor-fuselage coupling exists because the forces acting on the fuselage depend on the motion of the blades, and in turn the blade loads depend on the motion of the fuselage. Thus an existing, fuselage-only trim procedure originally developed at NASA Ames was extended into a fully coupled trim model. This was mainly accomplished by transforming the ordinary differential equations of motion of the blades into algebraic equations using a global Galerkin method, by appending the resulting set of nonlinear algebraic equations to the set of fuselage equations, and by solving the combined algebraic system simultaneously. Included in the solution of the trim problem was the steady state motion of the hub, which was then fed as a prescribed motion into the aeroelastic stability and response analysis. The model was used to generate the first analytical results ever for the aeroelastic stability of a hingeless rotor helicopter in a flight condition other than steady, straight, horizontal flight. Among the several conclusions of the study were that (i) level turning flight conditions are generally stabilizing, mostly because the increased aerodynamic loads on the rotor increase the lag damping, but (ii) descending steep turns are destabilizing, therefore aeroelastic stability considerations may limit the maneuver envelope of hingeless rotor helicopters.; and (iii) approximate models of turning flight conditions obtained by simulating straight flight with a weight coefficient increased by the expected load factor are conservative in level flight, but fail to capture the destabilization predicted in descending turns.

The mathematical model, initially based on linear incompressible aerodynamics only, was subsequently extended to include quasi-steady stall and compressibility effects on lift, drag, and pitching moment distribution. This was needed to improve the accuracy of the results in high speed and/or high-*g* flight conditions. The modeling of stall and Mach number effects was carried out by including in the analysis the steady portion of the Leishman-Beddoes dynamic stall model.

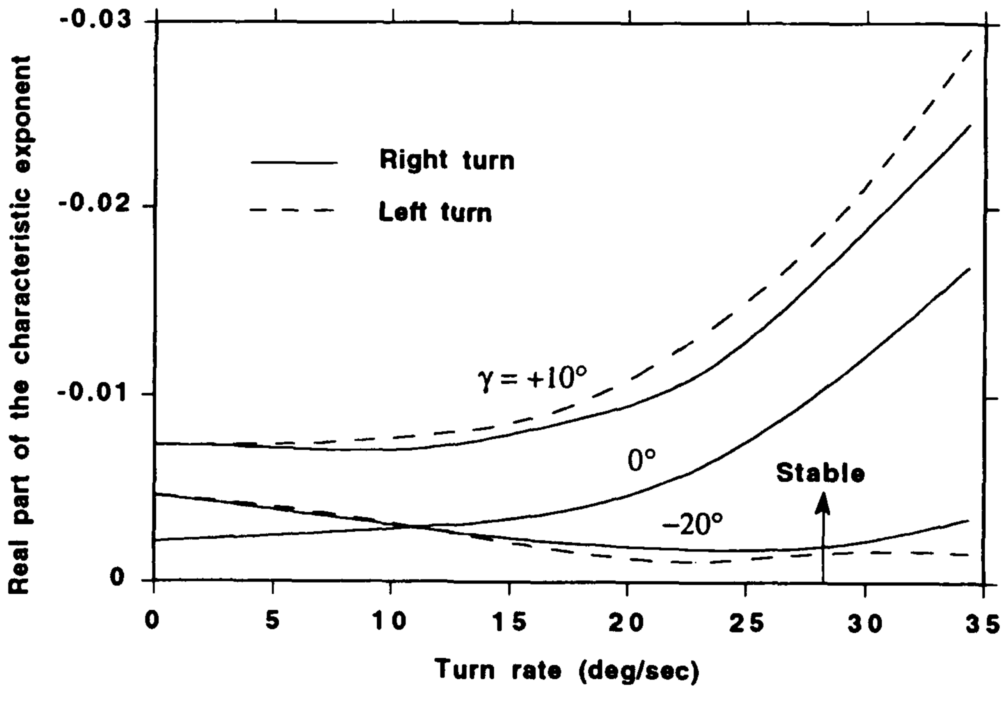


Figure 1: Stability of the second lag mode as a function of turn rate and climb angle γ for a hingeless rotor configuration; advance ratio μ=0.2.

The results of the study mostly confirmed those obtained using the simpler aerodynamic model, except that the effects of turning flight were felt at much lower turn rates. Stall was shown to increase the overall nonlinearity of the aeroelastic stability problem: for example, the characteristic exponents (which in Floquet theory determine the linearized aeroelastic stability of the system) were found to be very sensitive to the equilibrium position about which the linearization was carried out, when extensive stall area were present on the rotor disk. Because of the increased nonlinearity due to stall, bifurcating solutions appeared in the trim problem; the correct solution could be easily identified, however, based on physical considerations.

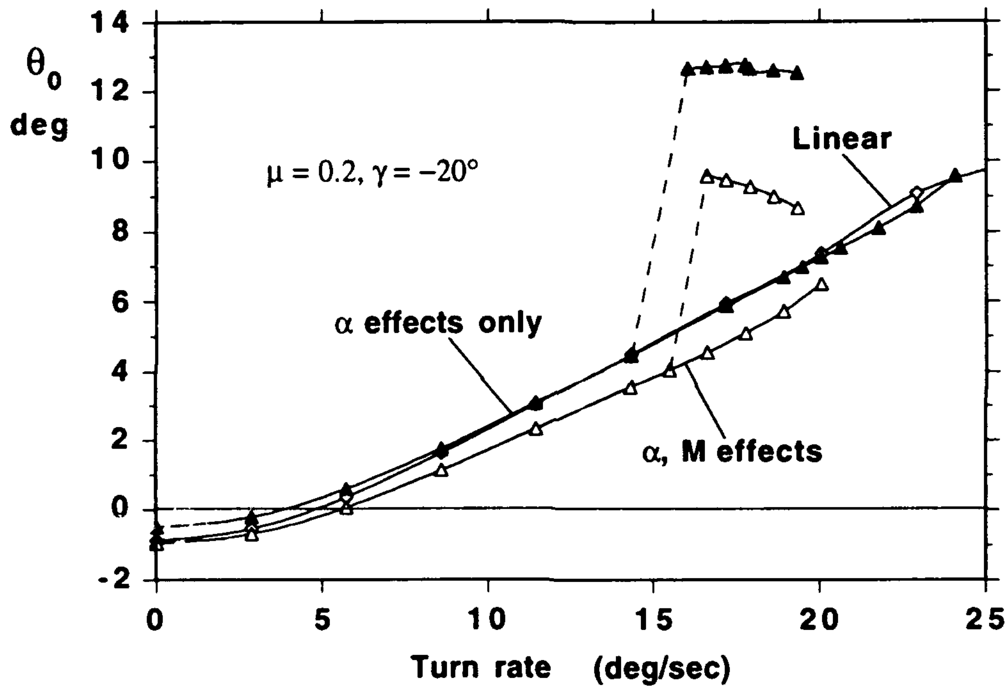


Figure 2: Trim value of the collective pitch as a function of turn rate for a hingeless rotor configuration; advance ratio μ=0.2, climb angle γ=-20°. The curves show the effects of steady stall and compressibility modeling. Bifurcations at high turn rate are evident from the plots.

With the inertia and aerodynamic operators of the aeroelastic problem already formulated in "implicit" form, a logical next step was to extend the implicit formulation to the structural operator as well, so as to have an analysis completely formulated in implicit form. (Strictly speaking, this extension was not required to extend the aeroelastic analysis into the flight dynamics area.) The implicit formulation is a generic framework that can be applied in principle to any beam theory. In this case it was applied to a Bernoulli-Euler beam theory which included nonlinearities due to moderately large elastic deflections. The study indicated the power and flexibility of the formulation which allowed, for example: (i) the use of nonlinear stress-strain laws provided in table look-up form, (ii) the incorporation of cross-sectional warping in a very simple way if the warping could be expressed as a polynomial function of the cross-sectional dimensions, and (iii) a much more convenient modeling of composite cross-sections. Additionally, most of the restrictions on the size of the elastic displacements could be removed, because such restrictions had been only introduced to simplify the algebraic manipulations required by the theory (through the definition and use of an ordering scheme). When an implicit formulation is used. most of those algebraic manipulations become unnecessary. Because in this way all the nonlinear geometric terms had been effectively retained, it was possible to study the effects of adding geometrically nonlinear terms beyond those traditionally associated with moderate deflection beam theories (such as those of Hodges and Dowell and of Kosen and Friedmann). Numerical calculations showed that these effects are essentially negligible in practical helicopter problems.

At this point, the rotor aeroelastic model included the main ingredients required to describe maneuvering flight with an arbitrary, but prescribed, hub motion. The next step, therefore, was to extend the model to include a full dynamic coupling between the rotor and the fuselage. This was accomplished by augmenting the rotor equations of motion with the nonlinear Euler equations of motion of the fuselage, to describe its six degree of freedom, rigid body dynamics. The solution technique of choice remained quasi-linearization, which provided simultaneously the steady-state periodic response of rotor and fuselage, as well as the Floquet transition matrix at the end of one period (equal to one rotor revolution) required to evaluate the small perturbation aeromechanical stability of the coupled rotor-fuselage system in forward flight. This coupled rotor-fuselage model has been recently completed. Portions of the analysis have been validated through comparisons with experimental results (hover tests by Ormiston and Bousman) and other simulation analyses (UMARC for aeromechanics in straight flight, and UM-Genhel for turning flight and rigid blades) A comprehensive analytical study of the effects of turns on aeromechanical stability and response is presently underway. The results generated by this analysis are the first published results on air resonance characteristics in flight conditions other than straight flight. The analysis can also generate linearized, time invariant mathematical models of the helicopter that can be used to generate the frequency response information required by the ADS-33C Handling Qualities specifications ("small attitude change" specifications).

The formulation of a multidisciplinary aeroelasticity/flight dynamics mathematical model was simultaneously pursued along a second path, with a traditional flight dynamics simulation model as its starting point. Compared with the aeroelasticity path previously described, a typical flight dynamics model tends to be more sophisticated in the aerodynamic description of the fuselage, and in the modeling of configuration features such as the pitch control chain and the propulsion system. On the other hand, the mathematical model of the rotor tends to be less sophisticated, and rigid blade approximations are common. On the solution side, aeroelastic and flight dynamic analyses typically share a focus on trim and linearized stability of constant coefficient representations, and tend to differ in the focus on the linearized stability of systems with periodic coefficients (for aeroelasticity) rather than on the transient response to pilot controls, including large amplitude maneuvers, on frequency response characteristics such as bandwidth and phase delay, and on the closed loop behavior in the presence of flight control systems.

The flight mechanics oriented research was initiated in response to a requirement of the U.S. Army AFDD, Ames Research Center, for a modification of the UH-60 simulation code Genhel, that would permit the extraction of high-order linearized mathematical models of the aircraft. These models would include rotor, inflow, and propulsion system dynamics and would be used for advanced flight control system design. The activity started in 1988 as part of a Consortium Agreement with Ames, continued throughout the period covered by this report, and constantly interacted with the more "aeroelasticity oriented" research described previously.

The mathematical model contained in Genhel was not formulated in first-order, state variable form. This did not affect the direct numerical integration of the equations of motion, but made it almost impossible to extract accurate linearized models by perturbing each of the states, and using finite difference approximations. The rotor equations were solved using an ad-hoc algorithm based on the assumption that the rotor motion was periodic. This was adequate for low frequency calculations, but could generate errors for high frequency phenomena, such as closed loop rotor-fuselage couplings induced by high-gain flight control systems. These, and other limitations were removed, and the formulation was recast in rigorous first-order form, so that high-order state-space models could be easily extracted. The current model includes up to 48 states which describe: (i) rigid body fuselage dynamics, (ii) flap and lag dynamics of each individual blade, plus a pseudo-torsion degree of freedom, (iii) inflow dynamics for main and tail rotor, (iv) propulsion system dynamics, including rotor RPM and engine thermodynamics, (v) downwash delays on tail surfaces and tail rotor, and (vi) actuator dynamics. If the flight control law introduces its own states (e.g. observer states, or time-varying compensators) these can be added to the overall linearized system.

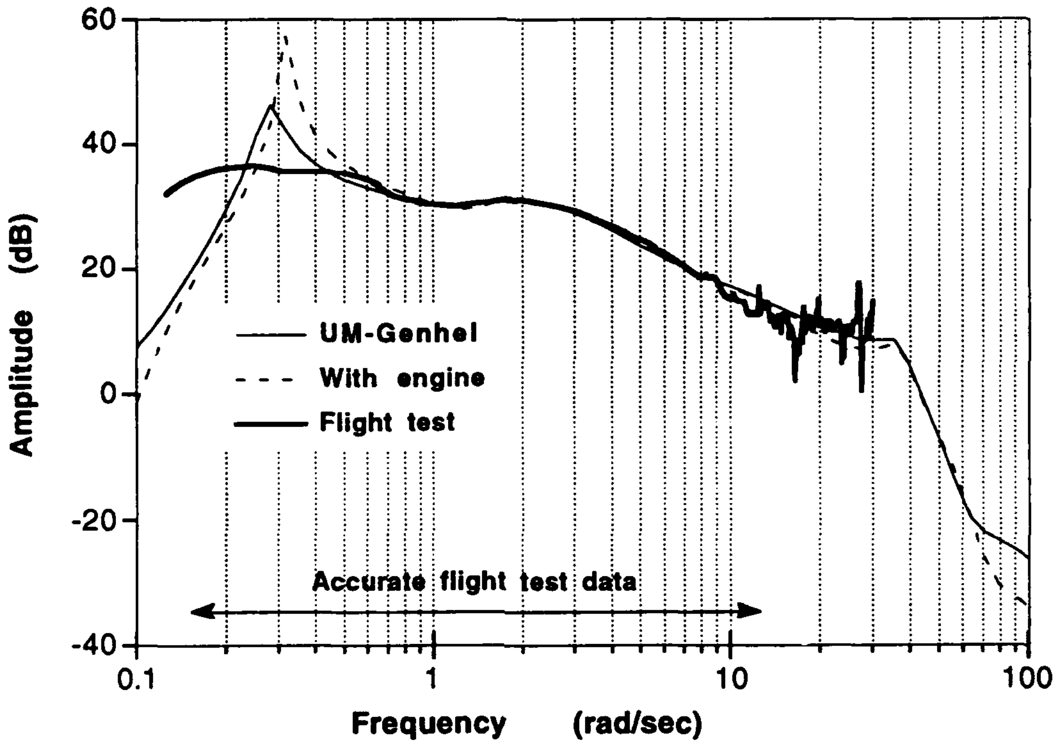


Figure 3: Frequency response of roll rate to lateral cyclic for a UH-60 flying at 80 kts, and comparison with flight test data.

A two phase coupled rotor/fuselage/engine trim procedure was developed for and added to the model. The first phase is largely based on the trim procedure used in the aeroelastic analysis, and outlined previously. The trim calculations can be refined, if necessary, in a second phase consisting of the solution of a nonlinear, two-point boundary value problem, in which the periodicity of the states is enforced through a preassigned number of rotor revolutions.

The mathematical model was validated in the frequency domain, by comparisons with frequency response plots obtained through nonparametric system identification techniques from flight tests of the Sikorsky UH-60. The trim procedure was also validated using UH-60 flight test data.

The mathematical models formulated from an aeroelasticity and from a flight mechanics point of view respectively, are currently being merged into a single multidisciplinary model that is suitable for the study of problems in both helicopter engineering areas. The generation of this interdisciplinary model presented special challenges, both in the formulation of the equations of motion and in the solution procedures, which will be presented in detail in future progress reports, and disseminated in upcoming conference presentations and journal publications.

While the bulk of the flight dynamics research in the 1987-1992 period consisted of the formulation, solution, and validation of mathematical models for helicopter simulation, additional activities were carried out in the following three areas: (i) formulation of design optimization problems, including flight dynamics considerations, (ii) investigation of dynamic coupling effects between rotor and propulsion system, and (iii) investigation of the effects of higher order dynamics (such as rotor and inflow dynamics) on helicopter flight control laws synthesized using modern multivariable control methodologies.

The objective of the optimization work was to determine whether it was possible to stabilize the phugoid mode of a hingeless rotor helicopter by tailoring the aeroelastic behavior of the rotor, and without additional stability augmentation systems. The problem was formulated as an optimization problem, with blade torsional stiffness, and cross-sectional offsets between elastic axis and aerodynamic center and elastic axis and center of mass, as design variables. The objective function to be minimized was the real part of the (unstable) phugoid eigenvalue. The behavior constraints were: (i) aeroelastic stability at a given advance ratio for the six lowest frequency coupled modes, (ii) blade vibratory loads at the root, in the rotating system, and (iii) a constraint on the transient response to longitudinal cyclic pitch (the so-called NASA "two-second requirement"). The results indicated that stabilization of the phugoid might indeed be achieved through an appropriate tailoring of the dynamic response of the blade (especially its aeroelastic couplings.)

The coupled rotor/propulsion system dynamics study was initiated to determine whether the aeroelastic stability characteristics of a hingeless rotor in hover were sensitive to the dynamics of the propulsion system. In fact, the engine dynamics generates changes in rotor speed, which are perceived by the rotor as excitations in the lag degree of freedom (which is typically the degree of freedom with the least amount of damping). The mathematical model was composed of: (i) a simplified representation of the flap-lag dynamics of the rotor, which was modeled with rigid blades with root springs and offset hinges, and with the hub assumed fixed (i.e. no dynamic rotor-fuselage couplings), (ii) a model of the T-700 engine, which included nonlinear differential equations to describe the thermodynamics and the dynamics of the engine, and (iii) a simplified fuel control system, consisting of a Proportional-plus-Integral controller in series with a second order transfer function simulating fuel flow dynamics (sensor, valves, etc.). The most important results were that: (i) propulsion system dynamics couples the motion of the individual blades, so that aeroelastic analyses based on the use of a reference blade cannot be used for this type of problems, and (ii) for typical values of the inertia of the rotating components and of the gear reduction ratio, the effect of the engine dynamics on the aeroelastic stability is fairly small; increasing inertia or gear ratio by a factor of 2-3 will decrease aeroelastic stability substantially.

The study of the effect of higher order dynamics on flight control laws was initiated to determine whether it is possible to design a flight control system based only on the 6 degree of freedom rigid body dynamics, and neglecting rotor and inflow dynamics. The multivariable feedback control methodologies used in the study were: (i) Linear Quadratic Gaussian with *Loop Transfer Recovery* (LQG/LTR), (ii) Eigenstructure Assignment with Loop Transfer Recovery (EA/LTR), and (iii) H-• . The design objective was to satisfy a representative subset of the ADS-33C Handling Qualities Specifications, which required, from a control system design standpoint, pole placement, frequency response loop shaping, and decoupling of the transient response to control inputs. The results indicate that neglecting higher order dynamics leads to unconservative designs: a control law that is predicted to provide Level 1 handling qualities (the best rating) when incorporated in a 6-degree of freedom simulation model, yields Level 2 or even Level 3 (the worst rating) handling qualities when incorporated in a more comprehensive simulation model that includes rotor and inflow dynamics as well. This is true also for "robust" control methodologies such as H-•: the uncertainty, or modeling error, introduced by limiting the plant model to the rigid body dynamics only, is too large to be managed successfully even by robust control methodologies.

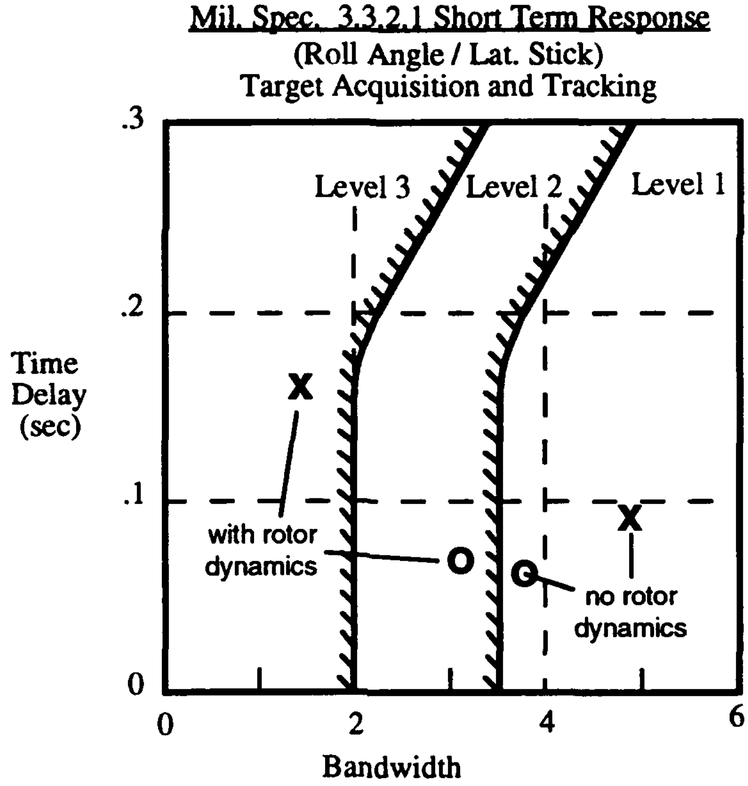


Figure 4: Effect of rotor dynamics on the design of a rate command control law, for a UH-60 in hover. The control law was synthesized using a 6 DOF rigid body model of the helicopter. The predicted performance is indicated by the points marked "no rotor dynamics". When the same control law is implemented in a 39-state simulation model which includes rotor and inflow dynamics, however, the helicopter performance is indicated by the points marked "with rotor dynamics". Thus the figure shows that neglecting rotor dynamics in the design of the control law is unconservative. The points marked with 'x' and 'o' were obtained with an H-infinity methodology, and an Eigenstructure Assignment methodology respectively.

5.0 COMPOSITE STRUCTURES AND MATERIALS

Composite materials offer many technological advantages over metals which are essential in the improvement of the performance of rotary-wing aircraft. These advantages include high specific stiffness and strength, increased resistance to fatigue and corrosion and potential for structural tailoring. However, the efficient use of composite materials necessitates a more complete understanding of their behavior under the applied loads.

Accordingly, the research effort at the University of Maryland has addressed key rotorcraft issues such as structural integrity, energy absorbency, and rotor blade modeling. Some of the significant results include 1) the understanding of failure mechanism of tapered structures including damage initiation and growth, 2) a structural tailoring technique that can delay or prevent free-edge delamination, 3) ply drop configurations for increased structural integrity of tapered laminated composite structures, 4) tapered composite structures for improved energy absorption under non-uniaxial loads, 5) a finite element formulation which can model accurately composite blades of complicated cross sections, taper and twist with stiffness couplings.

5.1 Structural Integrity

5.1.1 Structural Integrity of Tapered Composites

For the design of a flexbeam (bearingless rotor), composite materials are used for their high strength, high stiffness, superb fatigue characteristics, and superior damage tolerance characteristics. The flexbeam is required to be stiff at the hub and flexible at the blade. Because the structure is laminated, the span-wise bending stiffness can only be altered by changing either the orientation or the number of fibers along the length of the flexbeam. Plies are terminated internally at discrete locations to reduce the stiffness of the beam. This results in a taper.

At the beginning of this research, limited literature was available regarding the initiation and growth of damage in a tapered laminate. Initial experimental results at the University of Maryland indicated that delamination would occur in the tapered region and lead to catastrophic failure. Thus, the initial objectives of the research were: *To understand the failure mechanisms that lead to delamination onset and growth and to develop and implement structural tailoring techniques that will* *enhance the structural integrity of a tapered laminate by either increasing the load at which damage initiates or by decreasing the rate at which the damage grows or both.*

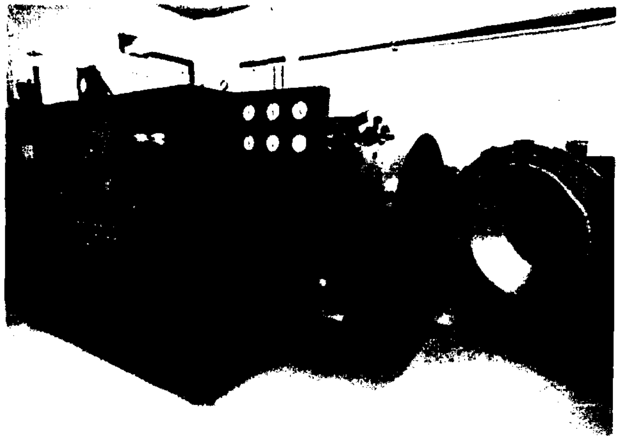
Both analytical and experimental approaches were taken. A finite element model was developed to accurately represent the tapered laminate to obtain a detailed description of the stress state. In addition to the resin-rich pockets that are formed at the ply drops, the model includes thin interply resin layers between the dropped plies and the continuous plies. This allows for the direct calculation of the interlaminar stress state as well as the application of isotropic failure criteria to the resin material. Each sublaminate in the laminate, which may consist of one or more plies, is modeled by a single layer of solid finite elements. Adjustments in the local taper angle and the elastic properties are made to account for irregularities such as ill-formed resin pockets, misaligned ply drops, and failed resin pockets commonly found in manufactured specimens.

Experimentally, the research has concentrated on a specific geometry of the tapered laminate. Tests involved three different stacking sequences of the belt and core plies. Subsequently, the effect of film adhesive layers on the structural integrity and the effect of different ply drop configurations under static and cyclic loads were investigated. Damage onset and growth was monitored via drops in the applied load during the test and via radiography at selected points in the test program. The data were correlated to the analytical model.

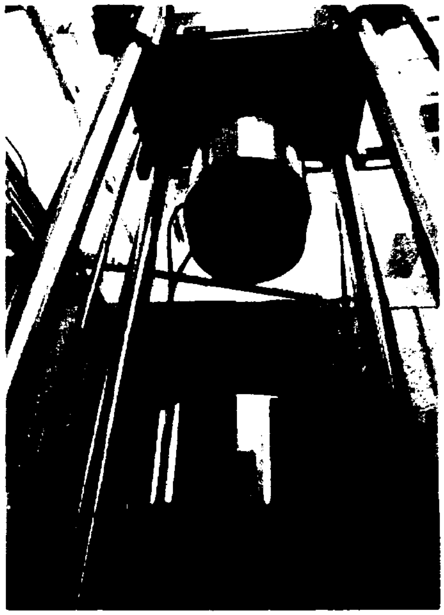
The finite element model indicates that damage initiates at the ply drop and not at the root of the taper. This was confirmed by the experimental evidence. The model also indicates that the effects of the taper and the stress-free edge are coupled. Therefore, a three-dimensional model of the tapered region is needed for adequate inclusion of the stress-free edge effects. Common artifacts of the manufacture and cure processes tend to increase the local effective taper angle, thus increasing the interlaminar stress state and decreasing the structural integrity. Finally, the analytical model indicates that failure of the resin pocket occurs prior to the onset of delamination.

Throughout the past five years the University of Maryland interacted with industry. An experimental program using with a toughened epoxy was supported by McDonnell-Douglas Helicopter Company. This effort was successful in understanding the failure mechanism under static and cyclic loadings and providing design alternatives that increase the structural integrity of tapered laminates. Sikorsky Aircraft has been supporting the development of analytical tools for design of tapered laminated structures .

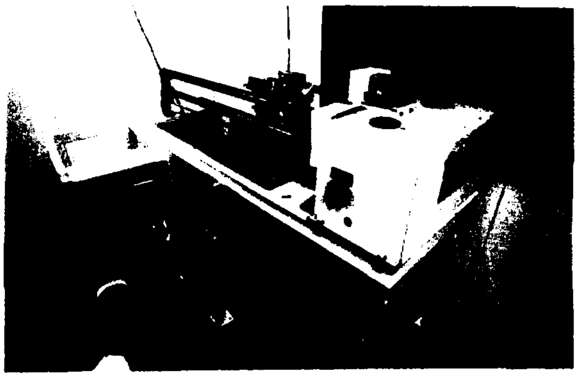
The effort of the past five years has culminated in an understanding of the important parameters and failure mechanisms in a tapered laminate.



Baron 3'-diameter, 4'-length microprocessor-controlled autoclave: 750 °F, 250 psi — General purpose fabrication of thermoset and thermoplastic composite specimens and structures

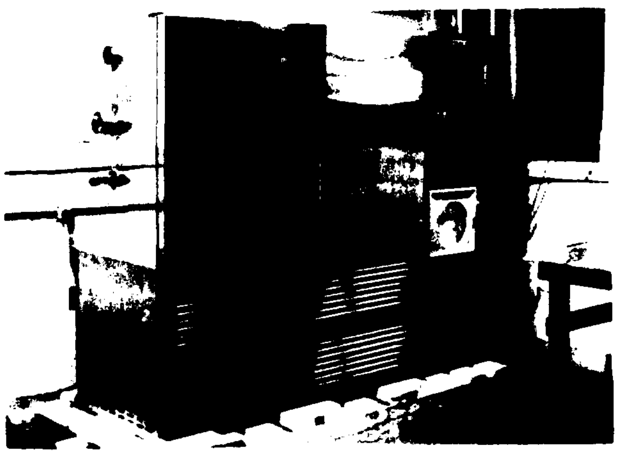


MTS 220,000 lbs uniaxial testing machine: static/cyclic; tension/compression; 16 channels A/D; computer controlled/data acquisition; hydraulic grips; compression platens — General purpose for axial, 4-point bending, and static crushing



McClean-Anderson 2-axis filament winder with instant return — Fabricate filament wound cylinders and helicopter blades

Blue-M humidity control cabinet: ambient—350 °F; ambient +5 —95% RH; 7 day monitor — Condition specimens for moisture absorption



Furthermore, this understanding has allowed extension of this research into other areas. In particular, the structural integrity of smart structures with embedded devices can be improved by using similar load redistribution as found in tapered structures. Typically, the plies in the plane of the device are terminated to accommodate the device. However, by terminating other plies through the thickness (this process is called interlacing), the critical interlaminar stress state can be reduced and relocated away from the interface between the embedded device and the host structure.

Specific areas of future recommended work include the development of efficient three-dimensional models of a tapered laminate under combined axial, bending, and torsional loads; the development of simplistic analyses that address specific phenomena; and the extension of the experimental data base to include combined loadings.

5.1.2 Structural Integrity of Flat Laminates

Delamination, an out-of-plane failure that can result from in-plane loading is a failure mode inherent in laminated composite structures. This is possible because of the three-dimensional nature of the stresses at and near a geometric or material gradient or discontinuity in a laminated structure. At a stress-free edge, the mismatch of the elastic moduli of the individual plies in a laminated structure results in interlaminar stresses that promote failure of the interface between the plies. Examples of stress-free edges in rotorcraft structures include edges of flexbeams, cutouts in the fuselage, and fastener holes.

> *The objective of this effort was to develop structural tailoring techniques to increase the structural integrity by decreasing the interlaminar stress state that causes delamination.*

In one of the techniques studied, the interlaminar stress state at the free edge is altered by removing material of some of the plies near the edge and either not replacing it, replacing it with film adhesive, replacing it with the same material at a different orientation. In this way, the macro response of the structure is unaltered; however, the local stress state at the stress-free edge is altered significantly. Thus, delamination at the stress-free edge can be prevented or delayed. However, the above structural tailoring techniques creates an internal edge. The interlaminar stresses at and near the internal edge were of such magnitude that damage occurred internally prior to free-edge delamination. Structural tailoring increased the structural integrity of the stress-free edge but decreased the structural integrity of the laminate internally.

Subsequently, a technique called fiber skewing was developed to avoid creation of internal edges. The orientation of the fibers in a layer of preimpregnated tape is altered by skewing the ply prior to curing. The orientation of the fibers in the majority of the ply are unaffected, thus global response is unaffected. Since the fibers are skewed in a continuous fashion, there is no weak interface. The experimental results demonstrated the ability of this technique to prevent free-edge delamination. A majority of the specimens tested indicated no damage prior to ultimate failure. Of those specimens that did indicate damage prior to ultimate failure, the damage occurred above the strain level at which delamination occurred in unaltered specimens and the postmortem investigation indicated little or no delamination in the failure surface. Thus, fiber skewing is successful in preventing or delaying free-edge delamination.

Related Publications

J. C. Fish and S. W. Lee, "Delamination of Tapered Composite Structures,"*Engineering Fracture Mechanics*, Vol 34. (1), pp. 43-54, 1989.

Abstract: The delamination of tapered composite laminates with multiple internal drop steps is investigated. Both experimental testing of glass-epoxy coupon specimens and finite element modeling of the tapered region are conducted. The average stress concept is applied to out-of-plane stresses from a finite element model. Delamination failure criteria are then used to predict strength based on ply failure and interply resin failure. Strength predictions based on interply resin failure using stress averaging distance of one ply thickness are found to correlate well with the experimental results. Delamination in the tapered laminates is due to interlaminar shear failure of the interply resin surrounding the last ply drop step.

J. C. Fish and S. W. Lee, "Three-Dimensional Analysis of Combined Free-Edge and Transverse-Crack-Tip Delamination," in Composite Materials: Testing and Design (9^{th} Volume), ASTM STP 1059, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 271-286.

Abstract: The effects of combining a localized free-edge delamination with a transverse crack in $[0/90_n]_s$ (n = 1, 2, 3, and 4) glass/epoxy laminates are investigated. A three-dimensional finite element model is used to calculate strain energy release rates associated with delamination growth. The effects of the assumed delamination size, transverse crack length, and thickness of the 90^o sublaminate on the strain energy release rate are determined. Transverse cracking significantly increases the potential for delamination growth, raising the strain release rate by as much as two orders of magnitude. Furthermore, the introduction of a transverse crack changes the involvement of the different strain energy modes so that the total strain energy release rate is dominated by the shearing modes with little opening mode involvement.

The total strain energy release rate increases for laminates with thicker 90° laminates, but it is relatively insensitive to the size of the delamination.

W. R. Pogue, III and A. J. Vizzini, "Structural Tailoring Techniques to Prevent Delamination in Composite Laminates," *Journal of the American Helicopter Society*, Vol. 35, (4), October 1990, pp. 38-45.

Abstract: An experimental study was performed to determine the effect of structural tailoring techniques such as edge alteration on the prevention of free-edge delamination. A total of 85 six-ply tensile coupons were manufactured from AS4/3501-6 graphite/epoxy and loaded monotonically to failure. Unaltered specimens served as the baseline and were compared with specimens with various edge alterations. These edge alterations include vertical ply drop, hybridization with an isotropic film adhesive, discontinuous angle alteration, and continuous angle alteration. The onset of delamination was monitored and the ultimate strength determined. Appropriate edge alterations were determined from the results of a finite element analysis. Edge alteration involving a discontinuity at the internal edge of a [±15/0]s laminate involving the second and fifth plies increased the ultimate strength and moderately increased the delamination initiation stress. For [0/±15]s laminates involving discontinuous edge alterations, the delamination stress was slightly increased; however, the ultimate strength was reduced. Postmortem analysis revealed that, in many cases, delamination did not initiate at the free edge of an altered specimen, rather the failure initiated at the internal edge. However, when a continuous angle alteration was used, delamination onset was never promoted and often delamination was prevented.

J. C. Fish and A. J. Vizzini, "Tailoring Concepts for Improved Structural Performance of Rotorcraft Flexbeams," *Composites Engineering*, Vol. 2 (5-7), 1992, pp. 303-312.

Abstract: Quasi-static tension tests were performed on tapered glass/epoxy laminates with internally dropped plies. In addition, a finite element analysis was conducted to determine the interlaminar stress states near the ply drop closest to the root of the taper. Four different internal ply drop configurations were examined which achieved the same transition in thickness. The delamination loads and corresponding bending stiffness losses were measured. The delamination onset loads varied by 38% and the bending stiffness retention varied by 56% among the internal ply drop configurations. Three of the four configurations delaminated in an unstable manner, while stable delamination initiation and growth occurred in one of the configurations. In general, a trade-off existed between the delamination strength and retention of bending stiffness. However, the configuration

which delaminated in a stable fashion had the best bending stiffness retention as well as intermediate delamination strength.

A. J. Vizzini, "Strength of Laminated Composites with Internal Discontinuities Parallel to the Applied Load," *AIAA Journal*, Vol. 30 (6), June 1992, pp. 1515-1520.

Abstract: A methodology to predict the strength of laminated composites with internal discontinuities parallel to an uniaxially applied load is developed. A quasi-three-dimensional finite element analysis is used to determine the state of stress at and near the internal discontinuity. Two techniques to predict the strength are developed. In one technique, the state of stress in a small resin pocket at the discontinuity is used with an isotropic failure criterion to determine the strength of the discontinuity. The other technique uses the in-plane state of stress around the discontinuity with a failure criterion based on an analogy with an individual ply. A limited number of specimens which had either a longitudinal ply drop or a material discontinuity were manufactured and tested in uniaxial tension. Damage initiation was detected via a load drop that corresponds to an increase in the compliance of the specimen. The observed response of the specimens agrees well with the predictions.

A. S. Llanos, and A. J. Vizzini, "The Effect of Film Adhesive on the Delamination Strength of Tapered Composites," *Journal of Composite Materials*, Vol. 26 (13), 1992, pp. 1968-1983.

Abstract: Film adhesive is used to suppress delamination in tapered glass/epoxy laminates. Two different stacking sequences with thin section layups of $[0_4/\pm45_2]_S$ and $[\pm45_2/0_4]_S$ containing three equidistant internal double-ply drops of 45 plies are investigated. Tapered specimens are manufactured and tested under quasi-static uniaxial tension. They are also modeled with and without layers of film adhesive. Thin interply resin layers are included in the model for direct assessment of the interlaminar stress state as well as for better modeling of the tapered region. The experimental study indicates an increase in the delamination onset load for the $[\pm45_2/0_4]_S$ specimens with film adhesive which corresponds to a decrease in the predicted stress state. However, the experimental study does not show any significant change in the delamination onset load in the $[0_4/\pm45_2]_S$ specimens even though the analysis indicates a decrease in the stress state. This indicates that for this stacking sequence, the taper is not the dominant contributor to the onset of delamination.

J. C. Fish and A. J. Vizzini, "Delamination of Ply-Dropped Configurations," to appear in 11th Symposium on Composite Materials: Testing and Design, ASTM STP, American Society for Testing and Materials, Philadelphia, PA.

Abstract: Unidirectional glass/epoxy tapered specimens were manufactured and tested under static tension and tension-tension fatigue. Four different ply-dropped configurations are studied with either grouped or dispersed plies and either staircased or overlapped dropped plies. At damage events in the static tests and at prescribed numbers of cycles in the fatigue tests, the specimens were placed in a cantilever fixture to determine their bending stiffnesses. The static tests indicated that the staircased-grouped and dispersed-overlapped specimens exhibited preferred structural performance by retaining their bending stiffness up to failure. The dispersed-overlapped specimen exhibited stable delamination growth. In addition, the fatigue tests indicated slow growth in the dispersed-overlapped with corresponding losses in the bending stiffness.

Related Presentations

W. R. Pogue, III and A. J. Vizzini, "The Effect of Structural Tailoring by Edge Alteration on Free-Edge Delamination," *Proceedings of the American Helicopter Society 44th Annual Forum*, Washington, D. C., June 1988, pp. 445-452.

Abstract: See Pogue and Vizzini, *Journal of the American Helicopter Society*, Vol. 35 (4), October 1990, pp. 38-45.

W. R. Pogue, III and A. J. Vizzini, "Structural Tailoring Techniques to Prevent Delamination in Composite Laminates," *Proceedings of the American Helicopter Society 45th Annual Forum*, Boston, MA, May 1989, pp. 489-496.

Abstract: See Pogue and Vizzini, *Journal of the American Helicopter Society*, Vol. 35 (4), October 1990, pp. 38-45.

W. K. Daniel and A. J. Vizzini, "Interlaminar Stresses in Composite Beams under Torsional Loading," *Proceedings of the American Society for Composites Fourth Technical Conference*, Blacksburg, VA, October 1989, pp. 974-981.

Abstract: Interlaminar stresses in a composite laminate under torsional loading were found by using anisotropic solid elements available in MSC/NASTRAN. The model was first qualified by comparing stresses with a quasi-three dimensional finite element model for tension loading of a $[\pm15]_S$ laminate. The model herein agreed well with the previous work. Interlaminar stresses were calculated for $[0/90]_S$ and $[\pm15]_S$ laminates subjected to a 1 N-m/m torsional moment resultant. For both laminates, the

interlaminar normal stress in the interply region on one side of the midplane was compressive until becoming tensile and increasing rapidly near the free edge. The tensile becoming compressive on the other side of the midplane. The interlaminar shear stress increased rapidly near the free edge for the $[0/90]_S$ laminate, but peaked at 2.5 MPa approximately one ply thickness from the edge for the $[\pm 15]_S$ laminate.

W. K. Daniel and A. J. Vizzini, "Prediction of Free-Edge Delamination Initiation in Composite Laminates under Torsional Loading," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference,* Long Beach, CA, April 1990, pp. 1253-1259.

Abstract: Laminates of $[\pm 15]_S$ and $[0/90]_S$ AS4/3501-6 graphite epoxy were analyzed using the solid elements in MSC/NASTRAN. In order to predict initiation of free edge delamination, an interply layer of isotropic resin was modeled using a single element through the thickness. Tension cases were analyzed so that the results of the model could be compared to experimental data; torsion cases were analyzed for prediction of delamination initiation. To predict delamination, the isotropic Mises failure criterion was used with interply stresses. The interply stresses were found to be too large, indicating that more than one element should be used through the thickness to model the interply layer.

A. J. Vizzini, "Strength of Laminated Composites with Longitudinal Discontinuities," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference,* Long Beach, CA, April 1990, pp. 1260-1269.

Abstract: See Vizzini, *AIAA Journal,* Vol. 30 (6), June 1992, pp. 1515-1520.

A. S. Llanos, S. W. Lee, and A. J. Vizzini, "Delamination Prevention in Tapered Composite Structures under Uniaxial Tensile Loads," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 31st Structures, Structural Dynamics and Materials Conference, Long Beach,* CA, April 1990, pp. 1242-1252.

Abstract: See Llanos and Vizzini, *Journal of Composite Materials,* Vol. 26 (13), 1992, pp. 1968-1983.

J. C. Fish and A. J. Vizzini, "Tailoring Concepts for Improved Structural Performance of Rotorcraft Flexbeams," *Proceedings of the American Helicopter Society Rotorcraft Structures Specialists' Meeting, Williamsburg,* VA, October 1991.

Abstract: See Fish and Vizzini, *Composites Engineering,* Vol. 2 (5-7), 1992, pp. 303--312.

A. D. Botting, A. J. Vizzini, and S. W. Lee, "The Effect of Ply-Drop Configuration on the Delamination Strength of Tapered Composite Structures," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 33rd Structures, Structural Dynamics and Materials Conference*, Dallas, TX, April 1992, pp. 40-47.

Abstract: Delamination suppression by altering the sequence of ply drops is evaluated for tapered glass/epoxy laminates. Two different stacking sequences with thin section layups of and containing drops of three sets of 45 plies are investigated. A finite element model using three-dimensional solid elements is constructed to evaluate the state of interlaminar stress in and around the ply drops. Tapered specimens are manufactured and tested under quasi-static uniaxial tension. For specimens of stacking sequence, delamination strength is dependent on the ply drop sequence. Structural tailoring of the ply drop region can result in a reduced interlaminar stress state and an associated increase in delamination strength. However, structural tailoring is ineffective in the specimens. The delamination strengths are insensitive to the ply drop sequence which indicates that the effect of the stress free-edge dominates the onset of delamination.

D. A. Singh and A. J. Vizzini, "Structural Integrity of Composite Laminates with Interlaced Piezoceramic Actuators," presented at Smart Structures and Materials, Albuquerque, NM, Feb. 1993.

Abstract: A three-dimensional finite element model is developed to analyze the interlaminar stress state surrounding an interlaced, active piezoceramic embedded within a unidirectional graphite/epoxy composite laminate. Interlacing increases the strength of composite structures with embedded actuators by redistributing the load around the piezoceramic and softening the material discontinuity between the piezoceramic and the composite structure. The analysis shows that interlacing results in as much as a 34.6% reduction in the magnitude of the maximum interlaminar tensile normal stress and a 25.2% reduction in the magnitude of the maximum interlaminar shear stress in the laminate. Moreover, the critical location of delamination initiation is removed from the interface between the piezoceramic and the composite material to a location away from the embedded actuator, thus maintaining the authority of the actuator after the onset of delamination.

A. J. Vizzini, "Delamination Strength of Realistic Tapered Geometries," presented at ASTM D-30 5th Symposium on Composite Materials: Fatigue and Fracture, Atlanta, GA, May 1993 (in review process).

Abstract: A finite element model of a tapered specimen was developed that incorporated naturally-occurring realistic geometries such as ill-formed resin pockets, unsymmetric and offset ply drop locations, varying ply thickness and

voids. Parametric studies were performed to determine the effects of these geometries that occur naturally in manufactured specimen. Ill-formed resin pockets increase the effective taper angle at the ply drop and cause a corresponding increase in the interlaminar stresses. In addition, the onset of damage location is dependent on the geometry of the ill-formed pocket. The effect of ply drops occurring unsymmetrically about the midplane is significant for offset values that occur as a result of the manufacturing process. Again the location for damage onset is dependent on the amount of the offset of the resin pocket. Voids or fracture within the resin pockets significantly increase the interlaminar stress at the ply drop and can decrease the structural integrity of the tapered element.

A. J. Vizzini and S. W. Lee, "Structural Integrity of Composite Flexbeams," *Proceedings of the American Helicopter Society 49th Annual Forum* , St. Louis, MO, May 1993.

Abstract: The structural integrity of composite tapered components is investigated. Several uncertainties within the research community are discussed. Finite element modeling and experimental evidence summarized from previous and present efforts are correlated to determine the location of the damage initiation, the interaction between the free edge and the taper discontinuities, the effect of realistic geometries, the extent and mode of damage growth, and the ability of simple physical models to explain the occurrence of the interlaminar stress state.

J. C. Fish and S. W. Lee, "Delamination of Glass Epoxy Laminates Based on Interply Resin Failure," *Proceedings of the American Society for Composites Third Technical Conference on Composite Materials,* Seattle, WA, Sep. 1988, pp. 242-252.

Abstract: The delamination onset strength of sixteen ply quasi-isotropic glass/epoxy laminates is studied. An alternate method of strength prediction based on failure of the interply resin layer between the delaminating plies is investigated. A strength-of-material approach, utilizing the average stress concept and a delamination failure criterion, is applied to interlaminar stress distribution obtained from quasi-three-dimensional finite element models. Good correlation between experimental and numerical results is obtained by basing strength on interply resin failure and using an interlaminar stress averaging distance of one-half of a ply thickness.

5.2 Multiaxial Energy Absorption

Crashworthiness was introduced in rotorcraft to increase the survivability of occupants. The goal is to maintain a livable volume, prevent fatal deceleration loads to the occupants, and prevent postcrash fires.

Composites had been demonstrated as potential materials in crashworthy structures as a direct result of the All Composite Airframe Program (ACAP). Much of the work performed by other researchers in the energy absorption of composite materials involved constant cross-section geometries and uniaxial characterization. Constant cross-section geometries are useful in determining the relative merits of different material systems. However, since the crash event involves complicated loadings, and the energy absorbency is a strong function of the damage mode that occurs, constant cross-section geometries under uniaxial loads may not provide adequate results.

> *The original goal of the research program was to demonstrate the potential errors in uniaxial characterization of constant cross-section geometries and to provide strategies for improved performance in the multiaxial loading environment.*

Initially, graphite/epoxy laminate cylinders were manufactured and tested under compressive load at an angle of inclination with respect to the center axis of the cylinder. As the angle of inclination increased, the damage modes around the circumference changed from an energy efficient delamination and splitting to bending and fracture. The sustained crushing stress decreased, indicating that, in the presence of a misaligned load, the energy absorbency of a composite structure is severely compromised.

The key to an efficient energy absorbent structure is to guarantee that the proper damage modes occur. If the load cannot be maintained to be uniaxial, then the structure must be designed to be more tolerant of the orientation of the load. Accordingly, truncated cones were manufactured, were loaded at various inclination angles, the damage modes were observed, and the energy absorbency was measured. Cones with a taper of 5° were observed to be the least sensitive to the angle of the applied load. The energy absorbency of the truncated cones under an inclined load was a function of the amount of the occurrence of damage modes about the circumference.

The research effort has resulted in a fundamental understanding of the effect of the local incidence angle of load on the energy absorbency of a laminated structure. The total energy absorbency of a structure with mixed damage modes was observed to be the sum of the energy absorbency of the individual modes. Accordingly, the design of crashworthy structures must account for loading conditions that may result in multiple energy absorbing modes. However, currently there is no method to determine the failure mode as a function of the geometry and the loading. Accordingly, the research effort at the University of Maryland is being directed to address this issue.

Related Publications

D. C. Fleming and A. J. Vizzini, "The Effect of Side Loads on the Energy Absorption of Composite Structures," *Journal of Composite Materials*, Vol. 26, No. 4, 1992, pp.486-499.

Abstract: Slightly tapered truncated cones were manufactured from graphite/epoxy preimpregnated unidirectional tape and were loaded in compression. Different amounts of side loads were introduced by orienting the loading axis away from the central axis of the cone. The cones were crushed under quasi-static conditions, and their energy absorption was measured. For small amounts of side load, the energy absorbency was improved; however, as the amount of side load is increased further, the energy absorption capability of the structure is reduced significantly. Furthermore, a tendency for the specimen to topple is observed as a result of the moment induced by the side loads which reduces the energy absorption properties even further.

D. C. Fleming and A. J. Vizzini, "Tapered Geometries for Improved Crashworthiness under Side Loads," *Journal of the American Helicopter Society*, Vol. 38, No. 1, January 1993, pp.38-44.

Abstract: Truncated cones of varying degrees of taper are manufactured from unidirectional AS4/3501-6 graphite/epoxy preimpregnated tape and are loaded in compression. Different amounts of side loads are introduced by orienting the loading axis away from the central axis of the cone. The energy absorption properties of the cones are measured under quasi-static conditions. The failure modes are determined around the circumference as a function of the loading and taper angles, and the energy absorbency is correlated to the observed failure modes. Constant cross-section specimens suffer significant losses in energy absorption in the presence of side loads; however, tapered specimens are less sensitive and do not suffer such significant losses. In fact tapered geometries provide greater energy absorption than constant cross-section geometries at moderate levels of side loads.

Related Presentations

D. C. Fleming and A. J. Vizzini, "The Effect of Side Loads on the Energy Absorption of Composite Structures," *Proceedings of the American Society for Composites, Fifth Technical Conference on Composite Materials*, June 1990, East Lansing, MI, pp. 611-620.

Abstract: See Fleming and Vizzini, *Journal of Composite Materials*, Vol. 26 (4), 1992, pp. 486-499.

D. C. Fleming and A. J. Vizzini, "Crash Worthiness of Composite Truncated Cones under Side Loads," Proceedings of the Sixteenth European Rotorcraft Forum, Glasgow, Scotland, paper # I.1.1, September 1990.

Abstract: See Fleming and Vizzini, *Journal of the American Helicopter Society*, Vol. 38 (1), January 1993, pp. 486-499.

D. C. Fleming and A. J. Vizzini, "Determination of the Energy Absorption of Composite Structures under Combined Loadings," Proceedings of the American Helicopter Society 47th Annual Forum, Phoenix, Arizona, May 1991.

Abstract: See Fleming and Vizzini, Journal of the American Helicopter Society, Vol. 38 (1), January 1993, pp. 486--499.

5.3 Finite Element Modeling of Composite Beams with Stiffness Couplings

Composite materials offer excellent opportunities for structural tailoring by selecting stacking sequences that exhibit stiffness couplings. Bending-torsional stiffness coupling can be used for aeroelastic stability of rotors while extensional-torsional stiffness coupling may be introduced to change the twist distribution in two-speed tilt rotors such as V-22 Osprey. Helicopter rotor blades can be modeled as beams because of their relatively slender geometry. Accordingly, an advanced and more sophisticated beam finite element formulation has been developed at the University of Maryland to model composite rotor blades with complicated cross-section, taper, pretwist and curved planforms. A key issue at the beginning of this research was the treatment of out-of-plane warping for beams with complicated cross-sections. The bulk of existing beam models assume that the warping displacement is proportional to a variable that is a function of the axial coordinates. This variable may be the twist rate or a generalized displacement to represent warping. However, these types of models cannot represent accurately the cross-sectional warping of composite beams with complicated cross-sections or with stiffness couplings.

In the finite element formulation developed at the University of Maryland, *cross-sectional warping* is handled by adopting the kinematics of deformation where a small one-dimensional warping displacement is superimposed over originally flat cross-sections of the beam. The undeformed cross-section is still assumed to be rigid in its own plane and its translation and rotation to be described in the three dimensional space. Accordingly, the formulation can represent accurately the out-of-plane warping of complicated cross-sections. The formulation also allows finite rotation and shear deformation since rotation angles are treated as independent variables. In addition, the constitutive equation was developed, including the effect of induced strain such as thermal or piezoelectric strain. A formulation consistent with the assumptions in the beam theory was developed for composite beams of arbitrary ply layups and cross-sectional shape.

The validity and effectiveness of the finite element formulation has been demonstrated through numerical tests of example problems. These include beams of single-cell, double cell, and open sections such as I-beams. Comparison with the numerical solution obtained by solid element models and experimental test results show excellent agreement. For dynamic problems it has been shown that the effect of warping on total kinetic energy is negligible. Thus it is feasible to apply static condensation and drastically reduce the problem size.

Related Publications

A. D. Stemple and S. W. Lee, "Finite Element Model for Composite with Arbitrary Cross-sectional Warping," *AIAA Journal*, Vol. 26 (12), December 1988, pp. 1512-1520.

Abstract: A finite element formulation has been developed to take into account the warping effect of composite beams. This formulation is to be used model combined bending, torsional and extensional behavior of composite beams. The new approach can model thin-walled beams with complicated sections, tapers and arbitrary planforms. The strain is assumed to vary linearly through the wall thickness. Warping effects are properly incorporated in the formulation by assuming small warping displacements superimposed over cross-sections in the deformed configuration. The formulation includes transverse shear deformations. Numerical tests of example problems demonstrate the validity and effectiveness of the present approach. Comparisons of the present formulation with a shell element formulation and an experimental observation show excellent agreement.

A. D. Stemple and S. W. Lee, "A Finite Element Model for Composite Beams Undergoing Large Deflection with Arbitrary Cross-Sectional Warping," *Int J Num Meth Eng*, Vol. 28 (9), 1989, pp. 2143-2160.

Abstract: A finite element formulation is developed to take into account the warping effect of composite beams undergoing large deflection or finite rotation. This formulation is used to model combined bending, torsional and extensional behavior of composite helicopter rotor blades. The new approach can model thin to moderately thick walled composite beams with complicated cross-sections, tapers and planforms. The warping effects are incorporated by assuming one-dimensional warping displacements superimposed over cross-sections normal to the beam axis in the deformed configuration of a shear flexible beam. The fixed or total Lagrangian description is adopted in the present formulation and the Newton-Raphson method is used to solve the non-linear equilibrium equation resulting from the finite element approximation. Numerical tests of example problems demonstrate the validity and effectiveness of the present approach.

F. Gandhi and S. W. Lee "A Composite Beam Finite Element Model with p-version Assumed Warping Displacement," *Composites Engineering*, Vol. 2 (5-7), 1992, pp. 329-345.

Abstract: A finite element model that can accurately represent the warping of composite beam is presented. A p-version formulation for the assumed warping displacement is used, with warping displacement, and higher order derivatives as nodal degrees of freedom over the cross-section. The p-version formulation allows higher-order approximation of warping and solutions of increased accuracy without mesh refinement. A consistent formulation for the incorporation of induced strain effects in composite beams is also included in the model. The model can be used for thin- to moderately thick-walled beams with complicated cross-sections, planforms, taper and pretwist. Numerical tests are presented for single-cell, two-cell and open sections, subjected to axial, bending and torsional loads, and temperature changes. The results shoe excellent agreement with three-dimensional solid element solutions.

Related Presentations

A. D. Stemple and S. W. Lee, "A Finite Element Model for Composite Beams Undergoing Large Deflection with Arbitrary Cross-Sectional Warping" Second International Conference on Rotorcraft Basic Research, College Park, Maryland, February 1988.

Abstract: see Stemple and Lee, "A Finite Element Model for Composite Beams Undergoing Large Deflection with Arbitrary Cross-Sectional Warping,"*Int J Num Meth Eng*, Vol. 28 (9), 1989, pp. 2143-2160.

F. Gandhi and S. W. Lee "A Composite Beam Finite Element Model with p-version Assumed Warping Displacement," *Proceedings of the AHS National Rotorcraft Structures Specialists' Meeting*, Williamsburg, VA, October 1991.

Abstract: see Gandhi and Lee, "A Composite Beam Finite Element Model with p-version Assumed Warping Displacement," *Composites Engineering*, Vol. 2 (5-7), 1992, pp. 329-345.

6. TECHNOLOGY TRANSFER

The Center has constantly and vigorously pursued a policy of technology transfer toward both industry and government laboratories. Consistent with its nature as a research and teaching institution, the Center has accomplished, and will continue to accomplish, technology transfer in several ways. The Center widely disseminates the results of research activities, both as presentations in technical conferences, and as publications in technical journals. At major rotorcraft related conferences such as the AIAA/AHS/SDM, the AHS Annual Forum, and the European Rotorcraft Forum, the Center has been a cl[illegible] leader among academic institutions. Over 60 journal publications and 70 conference papers have been generated since 1988 alone. There is a continuous flow of information directed toward industry and government laboratories. Every six months, the Center distributes a package of conference papers and dissertations to the technical management of all major manufacturers and government agencies. There are several computer codes (such as UMARC, UM-Genhel, and dynamic stall models) that are widely distributed to the rotorcraft community, along with new experimental techniques and experimental data. Several of the Center experiments are being used by industry and NASA as standard test cases for comparisons with theoretical models. All these activities are supplemented by the large number of personal contacts by faculty with their community counterparts. There are also many briefings given by the faculty to industry and laboratories each year, and in the future we intend to conduct group briefings at least once each year. The Center was host to two major conferences, the 2nd International Conference on Rotorcraft Basic Research in 1988, and a conference on Rotorcraft Dynamics and Aeroelasticity in 1991. We plan to host future conferences every two to three years.

7. EXPERIMENTAL FACILITIES

The experimental test capabilities of CRER have been developed over the past decade, and represent a high level of investment in state-of-the-art facilities for structural dynamics, aerodynamics, and composite structures research. CRER has two elaborate rotor rigs for the testing of rotors up to 6-ft. in diameter; a 4-bladed articulated rotor (Mach-scaled) and a 4-bladed bearingless rotor (Froude-scaled). Each test rig has remote shaft angle, and fly-by-wire cyclic and collective pitch capabilities. Standard rotor instrumentation includes a 6-component strain-gage balance, a torque disk, and a 60-channel slip ring unit. The bearingless rotor can be mounted on gimballed supports, with body pitch and roll degrees of freedom for ground/air resonance studies. CRER also has a capability to manufacture composite rotor blades, with embedded instrumentation. Hover tests are conducted on a dedicated hover tower facility, with forward flight tests conducted in the Glenn L. Martin 8.5-

by-11 ft. wind-tunnel. Other state-of-the-art facilities include a 10-ft. diameter vacuum chamber for dynamic studies on rotating composite beams, and a Composites Research Lab., which includes a 3-by-4 ft. autoclave, a filament winder, an environmental conditioning chamber, and a uniaxial testing machine. Photographs of the facilities and selected experiments are shown with progress summary of different research tasks.

8. EDUCATION

A key responsibility of CRER is the education of new generations of engineers, with a solid grounding in the fundamentals, and a thorough training in helicopter applications. Courses in Helicopter Aerodynamics (I and II), Helicopter Dynamics, and Helicopter Stability and Control, are part of the degree requirements for all the graduate students in the rotorcraft program.

Since its inception in 1982, CRER has awarded 87 M.S. and 22 Ph.D. degrees (the total of M.S. degrees include those awarded to students who have received or are pursuing a doctorate). Currently, 10 students are pursuing a M.S., and 22 a Ph.D. Of the total of 90 students who have received or are pursuing a graduate degree, 62 (69%) are U.S. citizens. Of the 44 doctoral students, 10 (23%) are non-U.S. citizens. Between 1983 and 1991 more American Helicopter Society Vertical Flight Fellowships have been awarded to Maryland students than any other university.

One important factor in attracting high caliber students has been the availability of prestigious ARO Graduate Fellowships. Since 1982, 23 students have been awarded such fellowships. Of the 11 students who have received a degree (6 M.S. and 10 Ph.D.) *all are currently employed in the helicopter field* (8 in industry, 7 in government research laboratories, 1 in academia). The other 7 students (David Fleming, Christopher Jones, Christopher Niggemeier, Christopher Park, Ih-Cheng Shih, Anne Marie Spence, and Anita Tracy) are all pursuing Ph.D. degrees. The ARO Fellowships, limited to U.S. nationals, are awarded to the best qualified applicants who express a strong interest in, and commitment to, helicopter engineering and intend to pursue a doctoral degree. Minimum undergraduate GPA for the award of a Fellowship is 3.8 out of 4.0.

The success of the Center in attracting additional support, and the caliber of its students, is further evidenced by the fact that almost *all 32 graduate students currently involved in the rotorcraft program are fully supported.* Sources of support include NASA, the Army laboratories, and U.S. helicopter manufacturers.

9. RESEARCH TEAM

Dr. Inderjit Chopra is the Director of the Center. Professor Alfred Gessow, former Director and now Professor Emeritus has guided the Center from its inception until 1991. The researchers identified in Table 2 are widely known to the rotorcraft community, are highly productive, and are a balanced group representing different disciplines of rotorcraft technology. Listed are seven full-time faculty, one of whom is a minority, and one a full-time rotorcraft researcher. In addition, two dedicated research engineers supported the experimental program. Three other faculty are expected to join our team, one in Smart Structures, one in computational fluid dynamics, and one in either acoustics or controls. Center personnel are highly committed to rotorcraft education and research, and play a leading role in the activities of the AHS. Surpassing any other academic institution, CRER members are currently serving on five AHS technical committees. During the period of the most recent CRER grant, members have contributed a total of 26 articles in 15 issues of *J. of the AHS*.

Researcher	Specialty	Experience
I. Chopra (Director) Professor and Distinguished Researcher 92-93 Sc.D. (MIT) Fellow AIAA	Dynamics	1977-81 NASA Ames/Stanford University, rotorcraft research. Joined Maryland in 1981. Published over 90 journal articles and reports on helicopter dynamics, controls, composites and optimization: experimental and theoretical
A. Gessow Professor Emeritus Founding Director (82-91) Highly respected among international helicopter community, Author of a Classic Helicopter Textbook Fellow AIAA Hon. Fellow AHS	Aerodynamics	1944-59 NASA Langley 1959-80 NASA Headquarters as Research Administrator 1981-89 Professor and Chairman of Department of Aerospace Engineering Founding Editor of AHS Journal 1958-59 Technical Director, AHS 1958-59 Published over 65 articles and reports on helicopter aerodynamics and flight mechanics, and other aerospace topics
S. W. Lee Professor Ph.D. (MIT)	Composite Structures	Joined Maryland in 1979. Published over 60 journal articles and reports in structural mechanics and composite structures
R. Celi Assoc. Professor Ph.D. (UCLA)	Flight Dynamics, Dynamics	Joined Maryland in 1987. Published over 35 journal articles and reports related to rotorcraft dynamics, flight dynamics and controls and optimization
A. J. Vizzini Assoc. Professor Ph.D. (MIT)	Composite Structures	Joined Maryland in 1986. Published over 35 journal articles and reports related to delamination and crashworthiness
J. G. Leishman Asst. Professor Ph.D. (Glasgow)	Aerodynamics	1983-86 Westland Helicopters. Joined Maryland in 1986. Published over 55 journal articles and reports in experimental and theoretical unsteady aerodynamics, and rotary-wing aerodynamics.
F. Tasker Asst. Professor Ph.D. (U of MD)	Dynamics	Joined Maryland in 1990. Research experience in helicopter dynamics and system identification
R. Chandra Asst. Research Scientist Ph.D. (IISc)	Composite Structures, Dynamics	1966-87 Scientist at NAL Bangalore. Joined Maryland in 1987. Published over 65 journal articles and reports on fracture mechanics, composite structures and rotor dynamics
G. S. Bir Research Assoc. Ph.D. (U of MD)	Dynamics	Joined Maryland in 1991. Research experience in rotor stability, gust response, and formulation of comprehensive rotor analysis